Multi-Parton Interactions in Experiments

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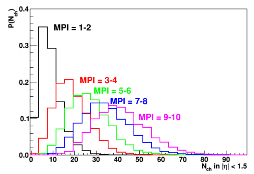
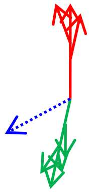
This Lecture

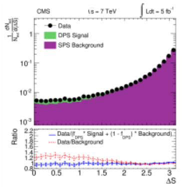
- Discuss measurements sensitive to or related to multi-parton interactions
  - Available observables (soft and hard)
  - Definition and measurement procedure
    (including selected details how to reproduce them)
  - Results and interpretation
  - Influence of MPI



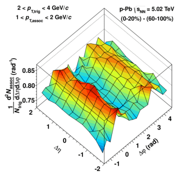
Multiplicity distributions



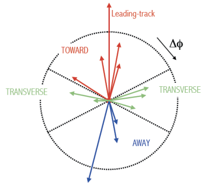
Uncorrelated Seeds (minijets)



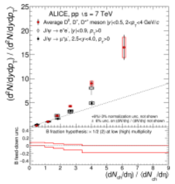
Double Parton Scattering



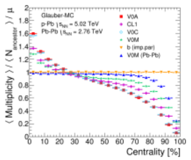
Collective Phenomena



Underlying Event



Hard Probes vs. Multiplicity

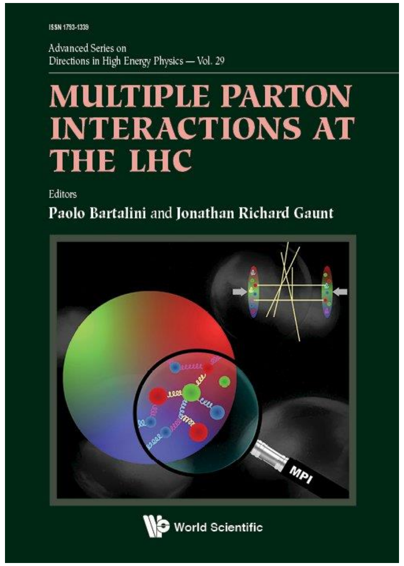


Multiplicity Biases

Further Reading

- Multiplicity
  - JFGO, PhD thesis, link
- Underlying Event
  - Sara Vallero, PhD thesis, link
- Uncorrelated seeds / minijets
  - In pp: Eva Sicking, PhD thesis, link,
  - In p-Pb: Emilia Leogrande, PhD thesis, link
- Hard Probes vs. Multiplicity
  - Javier Blanco, PhD thesis, link
- Concepts of multiplicity biases
  - Phys. Rev. C 91 (2015) 064905, arXiv link

- Multiple Parton Interactions at the LHC, ISBN: 978-981-3227-75-0



Multiplicity Distributions

Multiplicity Distributions

cities. The present availability of bubble-chamber facilities at Serpukhov, U. S. S. R., and at Batavia, U. S. A., has consequently made available for the first time accurate measurements of topological cross sections for very high-energy proton-proton collisions (50–300 GeV/c). In this

Fixed target collisions
→ cms: 10-24 GeV
Find the math here

- Multiplicity distribution $P(N_{ch})$ = probability that event has certain (charged) multiplicity
  - Within p_T and η phase space (due to detectors)
- Very sensitive to MPI

$P(N_{ch})$ vs. N_{ch}

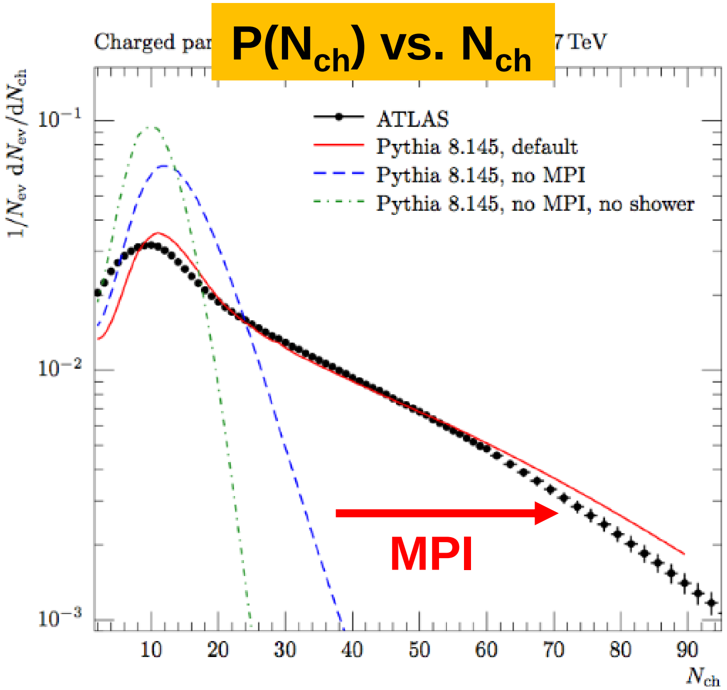
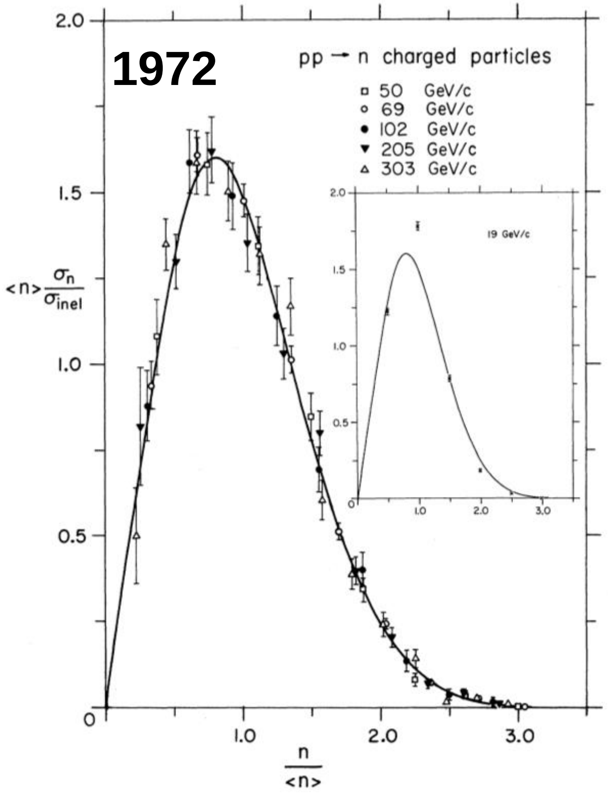


Figure: E. Nurse

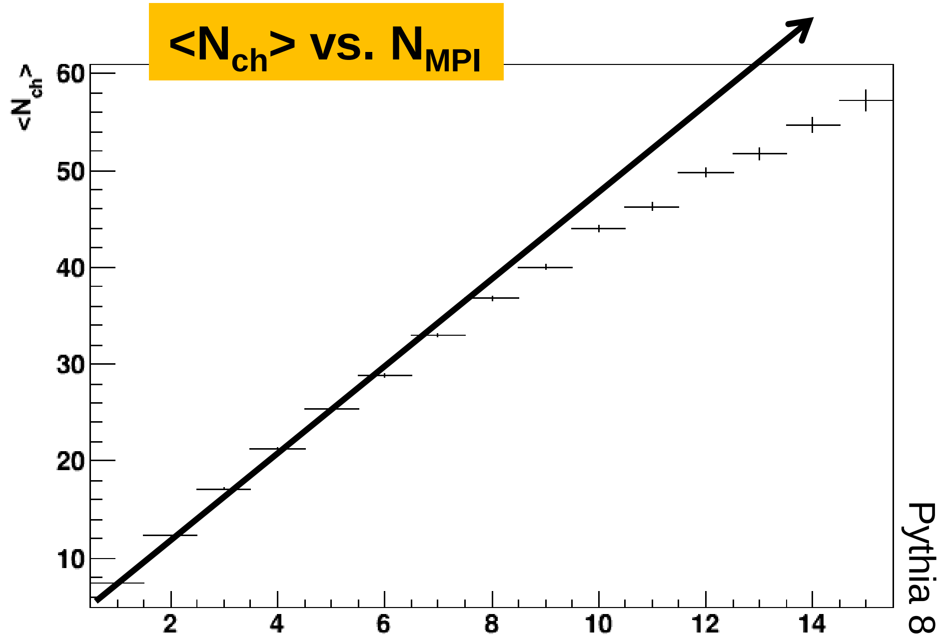


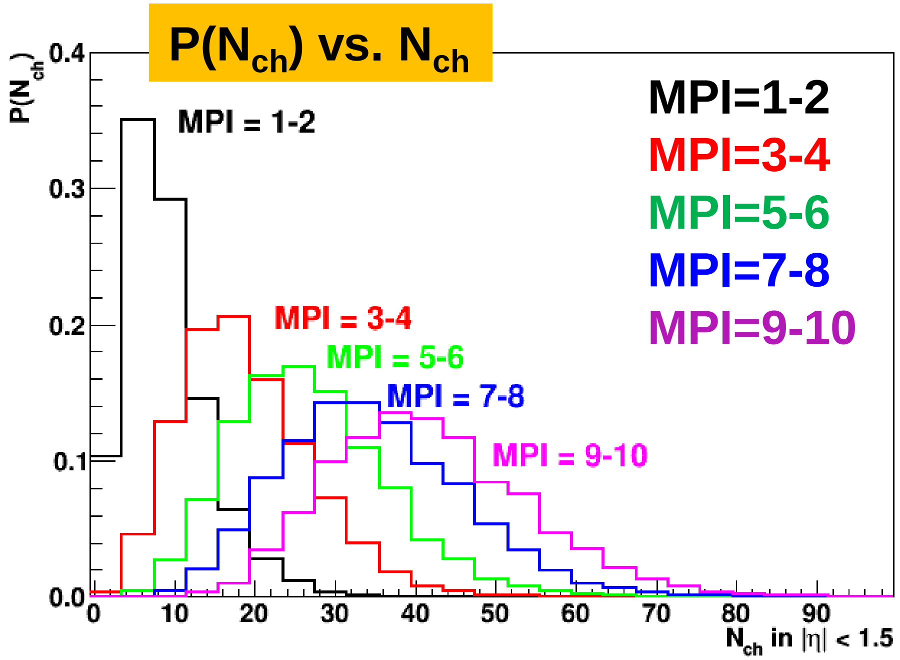
PRL29(1972)24

Multiplicity vs. MPI

- $\langle N_{ch} \rangle$ grows almost linearly with #PI
- Multiplicity distribution strongly depends on number of PI
  - Larger values not reached with few PI
  - Small values not reached with many PI

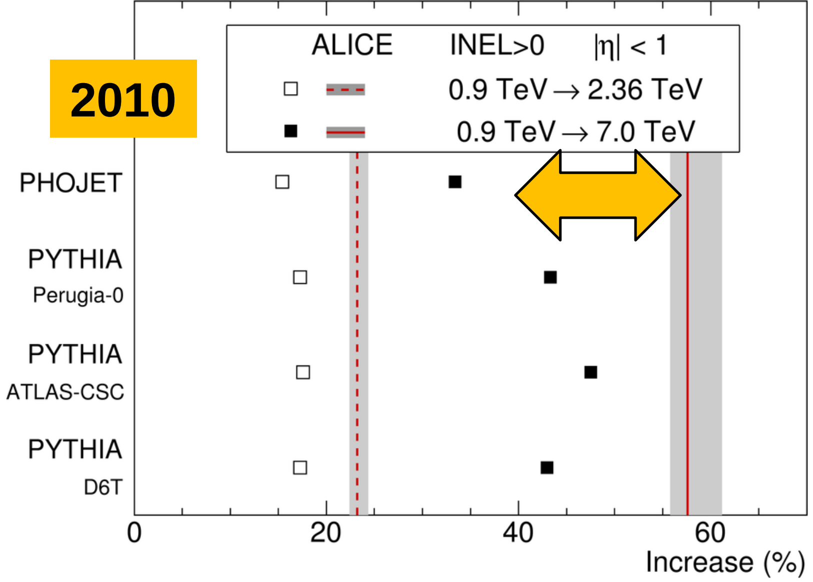
- Multiplicity distribution, in particular its tail, has large influence on MPI related parameters in MC tuning
- Unfortunately, not possible to measure $P(N_{ch})$ as a function of #PI





Average Multiplicities

- Average multiplicities at LHC energies
  - Faster increase than expected by MCs
- Indication for higher MPI activity
- MCs retuned affecting MPI
  - p matter distribution → affects impact parameter distribution
  - $p_{T,min}$ ($\sqrt{s}$)



EPJC 68 (2010) 345

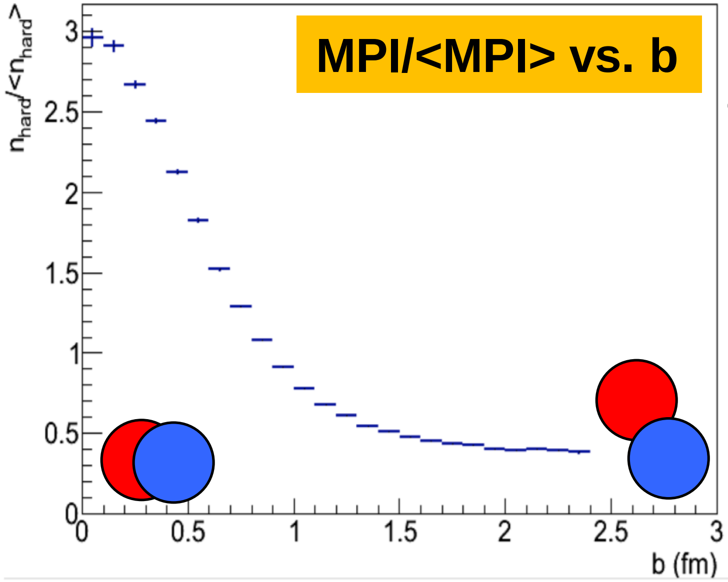
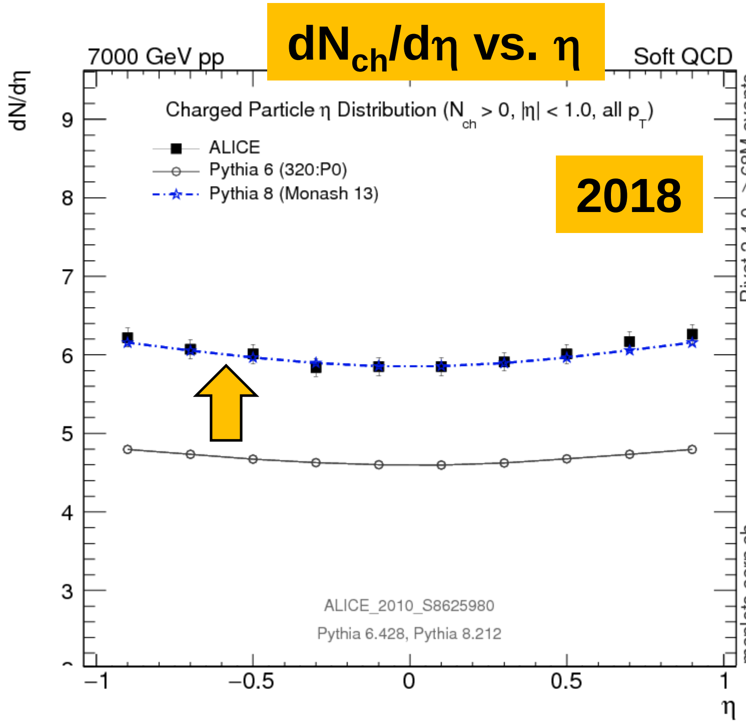


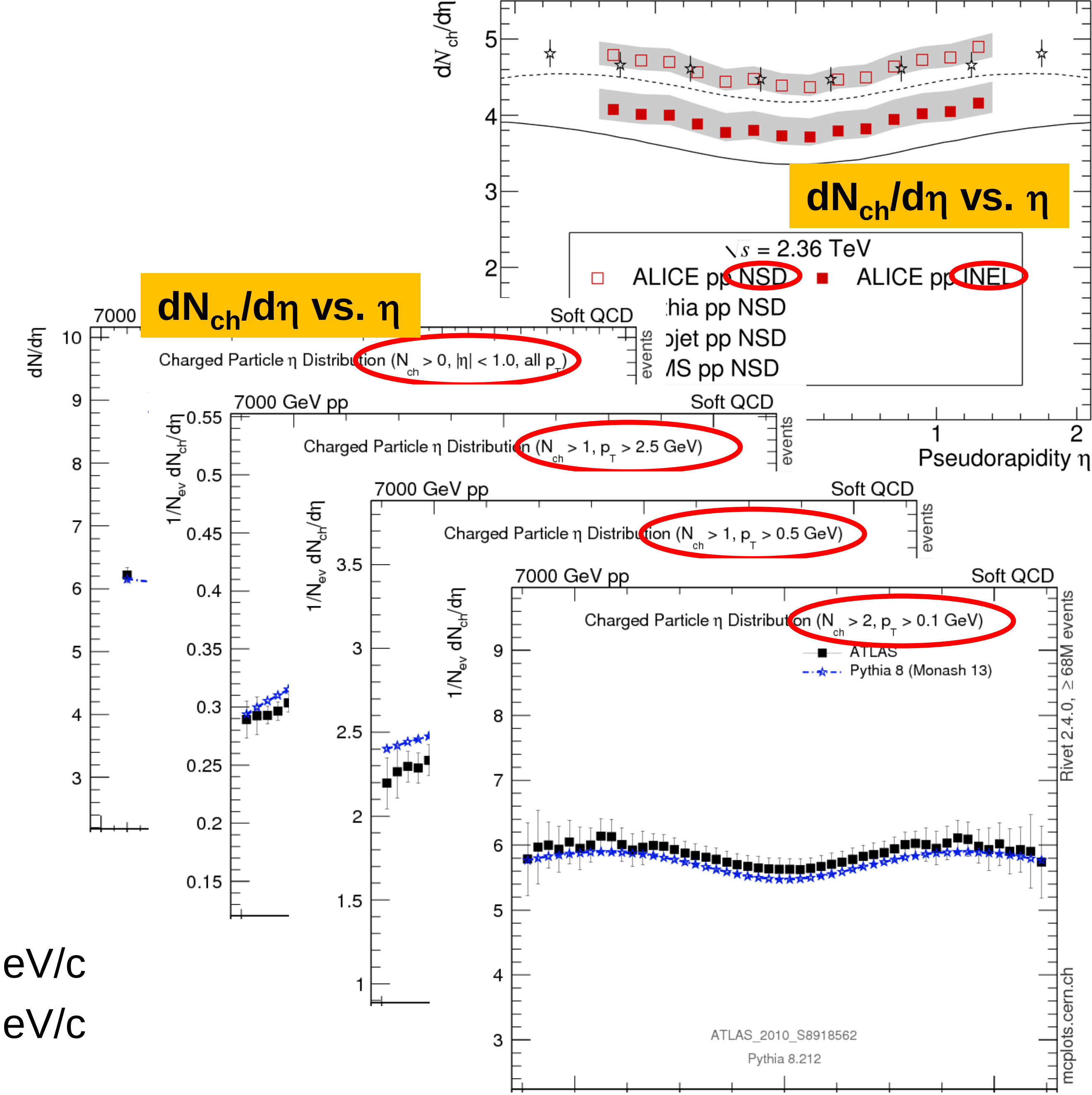
Figure: Andreas Morsch



mcplots.cern.ch

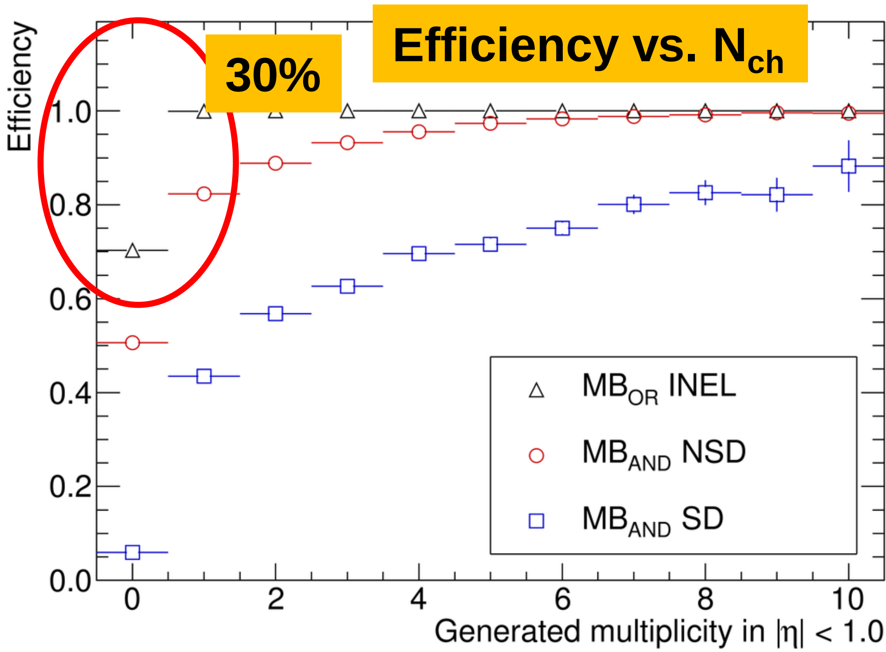
Event Classes

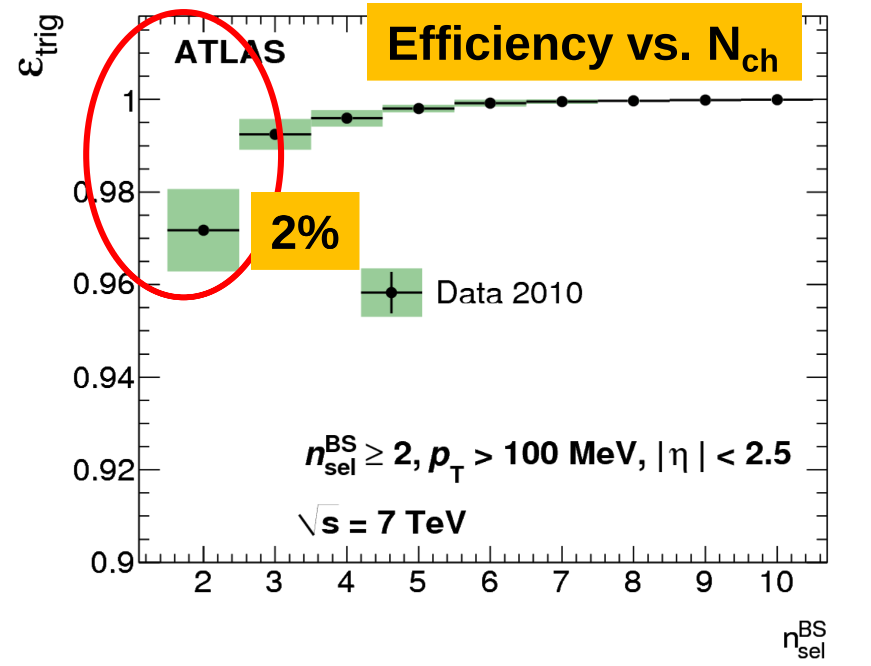
- Inelastic collisions
  - Non-diffractive and diffractive
  - Single and double diffractive, …
  - Some not measured
- Traditional classes: inelastic ("INEL") and non-single diffractive (NSD)
- Large uncertainties in corrections
- Avoided by particle-level definitions
  - At least N particles within phase space
- Examples
  - ALICE INEL>0: N_{ch}>=1 in $|\eta| < 1$
  - ATLAS: N_{ch}>=1 in $|\eta| < 2.5$ and $p_T > 0.5$ GeV/c
  - ATLAS: N_{ch}>=2 in $|\eta| < 2.5$ and $p_T > 0.1$ GeV/c

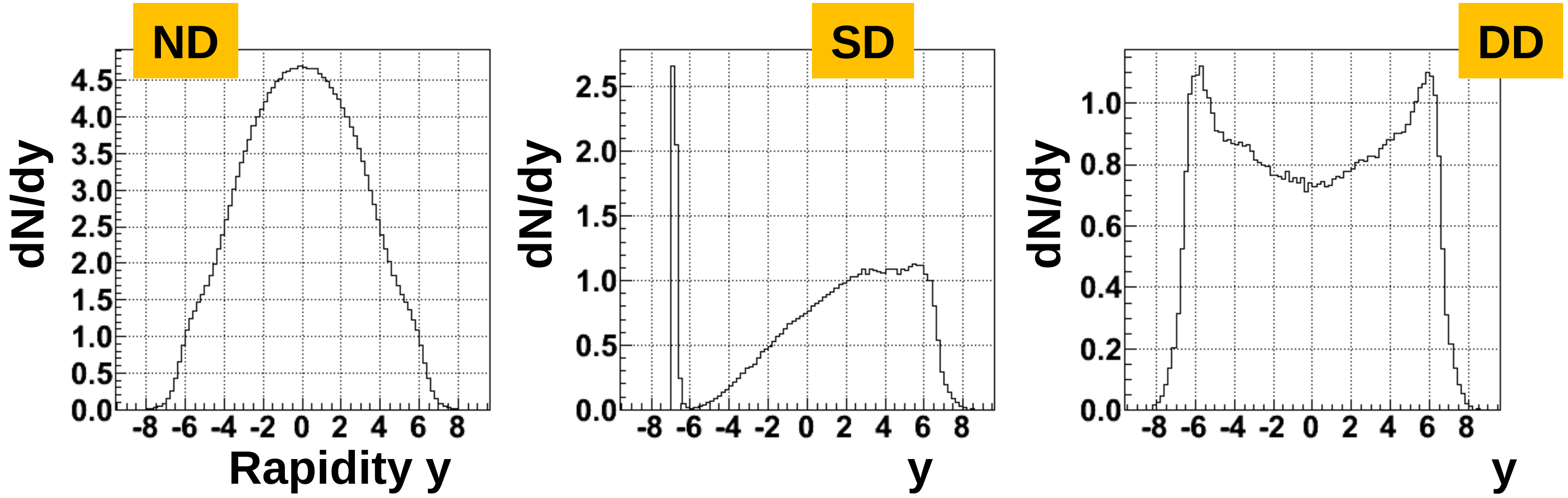


Event Classes & Triggers

- Event types have different topologies
- Non triggered fraction MC dependent
- Particle-level definition reduces not triggered fraction
  - Reduces overall uncertainties



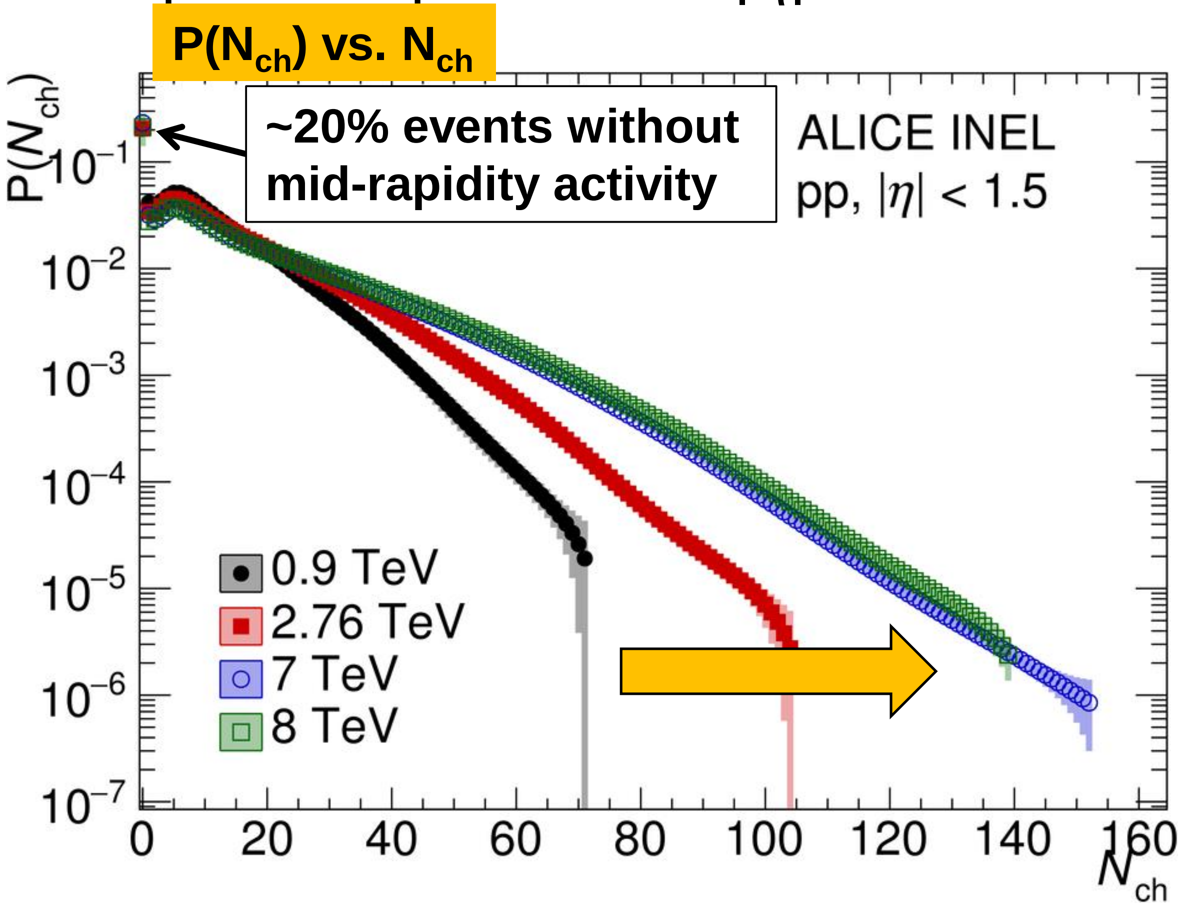




Multiplicity Distributions

- Tail widens with √s
- Up to 150 particles in |η| < 1.5

- Agreement among experiments over 5 orders of magnitude



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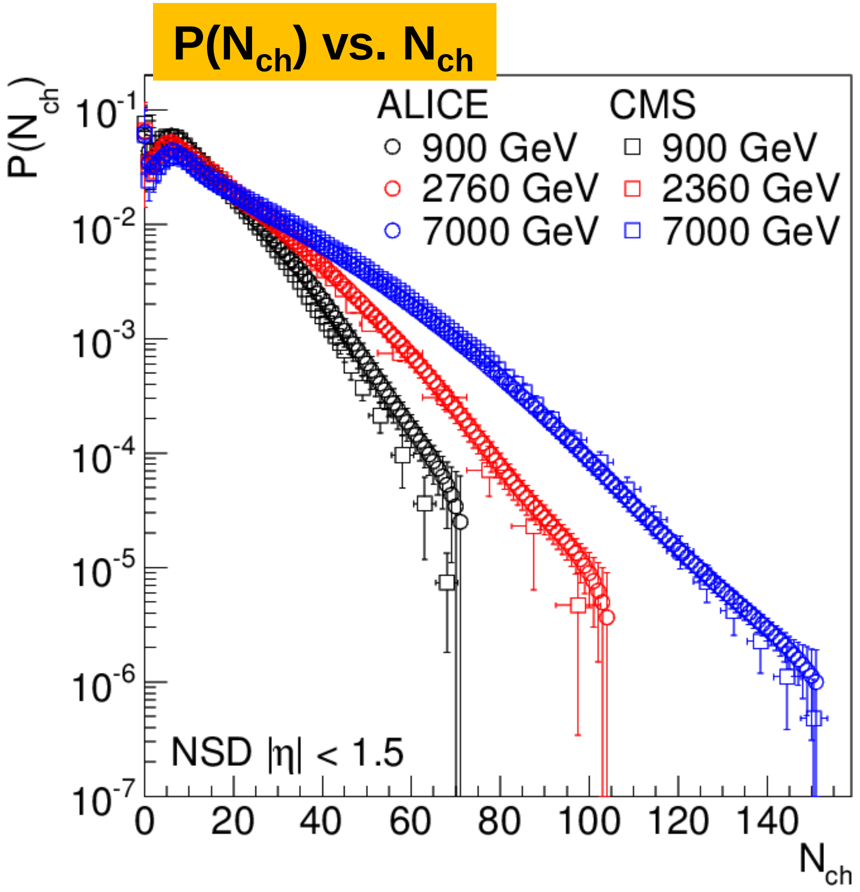
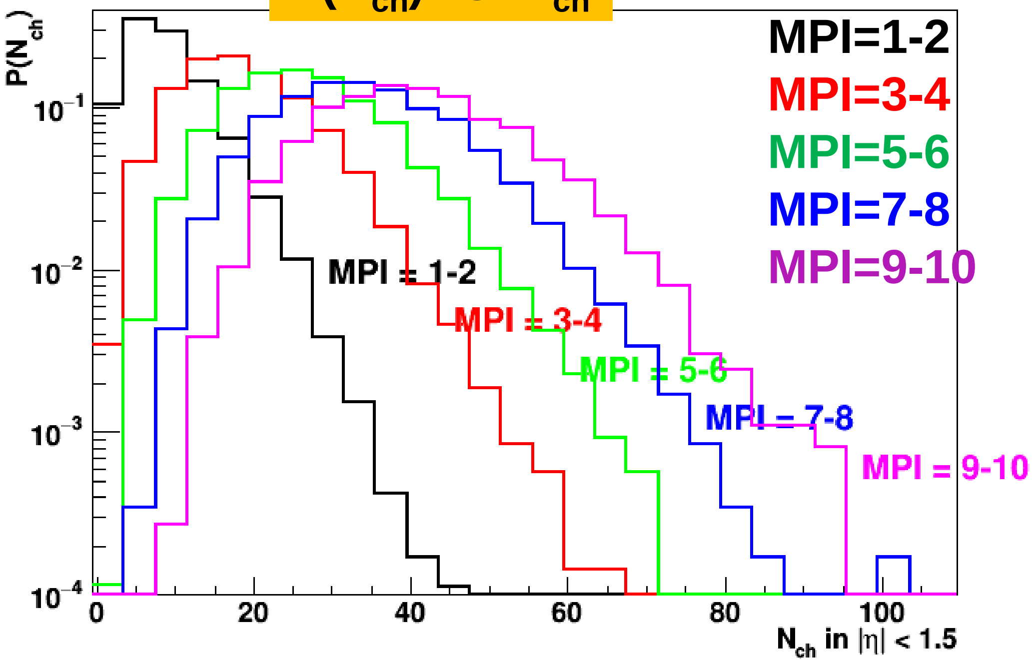


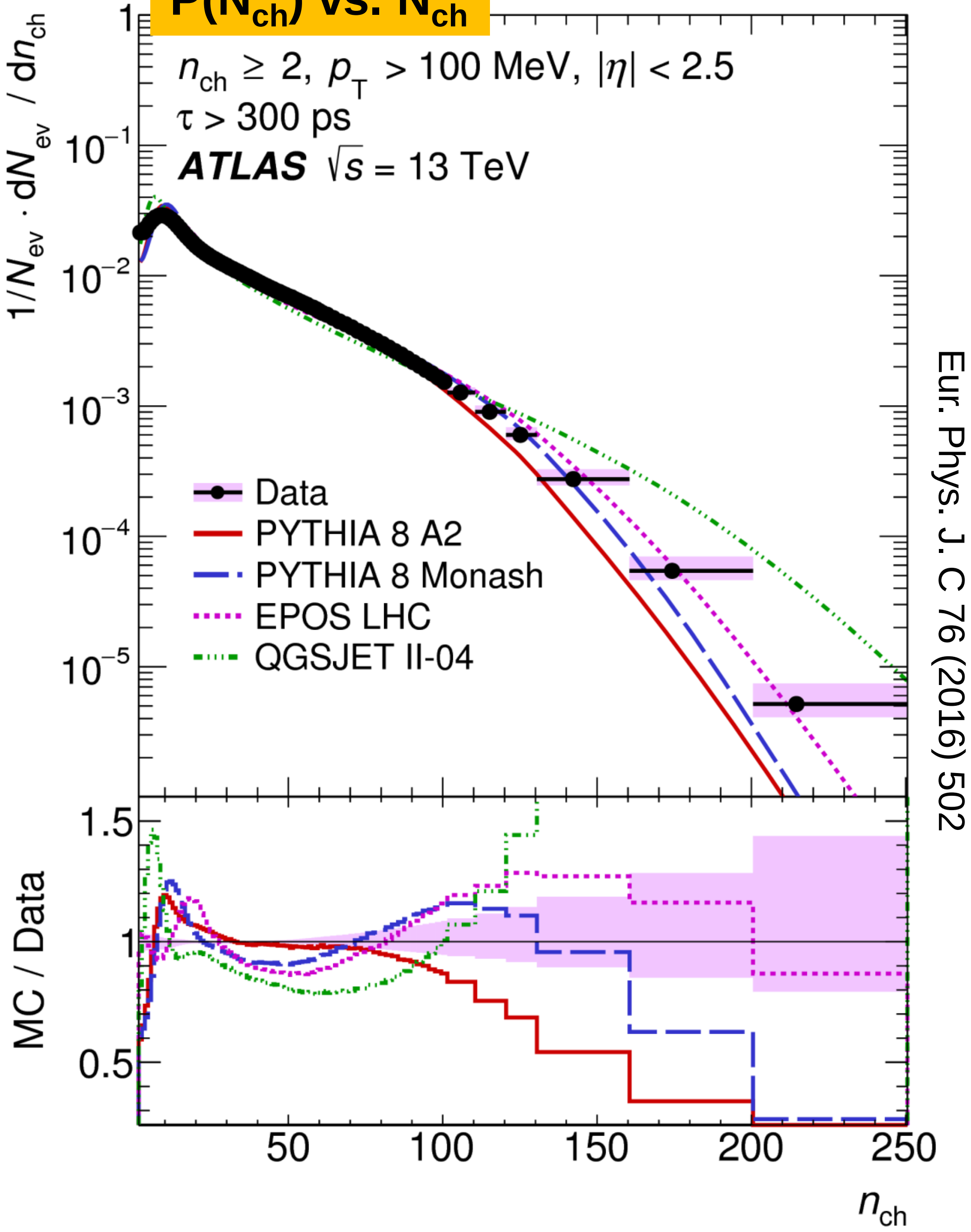
… and MCs

- Even state of the art MCs have a hard time for an exact description
  - Deviations of 20…50% easily occur
- Recap: tail is sensitive to large number of PI

P(N_{ch}) vs. N_{ch}



P(N_{ch}) vs. N_{ch}



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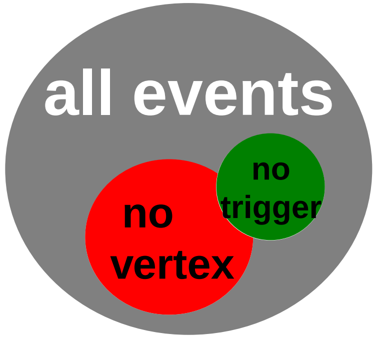
Corrections

How to measure

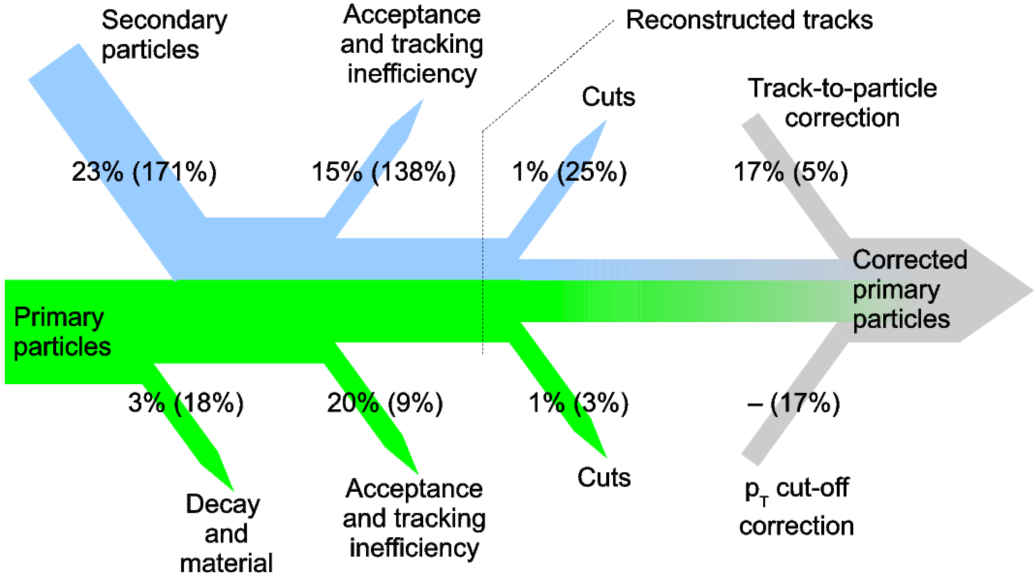
- Published multiplicity distribution != raw measurement
  - Usually causes lots of stress ☺
- Event-level corrections
  - Events skipped by trigger or vertex reconstruction
  - Migration in and out of desired event class



- Track-level corrections
  - Efficiency, secondaries
- Resolution
  - Track level (p_T) and event level (N_{ch}) → unfolding

Unfolding is an important concept, I use the example of the multiplicity distribution to introduce it here

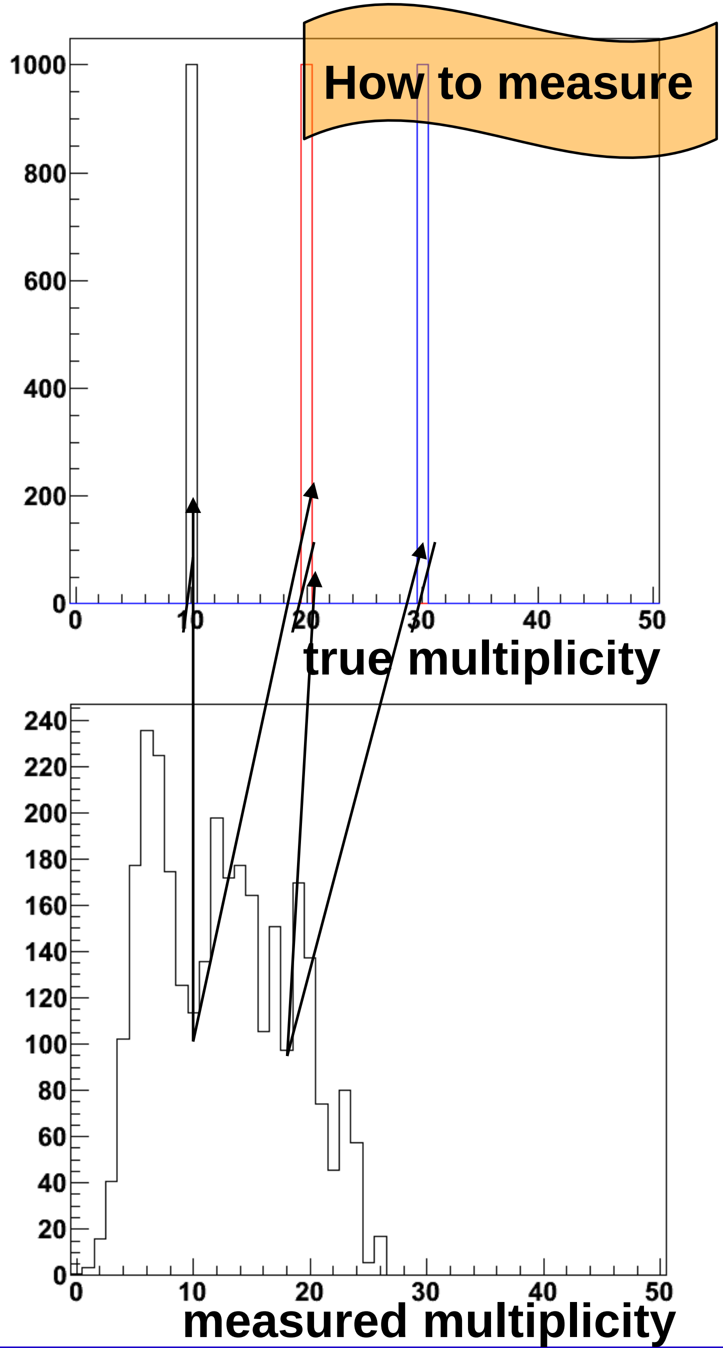
Example for ALICE SPD (TPC)



Unfolding

- Unfolding is
  - the estimation of a probability distribution for which (usually) no parametric form is available
  - where the data are subject to additional random fluctuations due to limited resolution
- Sometimes discussed as *inverse problem*, sometimes called *deconvolution* and *unsmearing*

- Unfolding
  - reverts bin flow (i.e. tries to recover information which you don‘t have)
  - assigns events or tracks in a reconstructed bin to their originating (true) bin on a statistical basis
  - → probability distributions are transformed
  - → no information about the origin of a *single* event is obtained



Unfolding - Mathematically

How to measure

- Measurement = folding with detector response
- Almost all practical purposes
  - Binning, discrete case → matrix / vector notation
- Unfolding
  - Inversion of the folding by the detector
  - Discrete: Inversion of a matrix
- T (M) is the expectation value of the true (measured) distribution
- One measurement provides M* for which E[M*] = M
- Based on M* we want to find an estimator T* for T
  - Should be unbiased, i.e. b = E[T*] – T = 0
  - Smallest variance as possible
- NB: this formulation neglects background

$$f_{meas}(x) = \int R(x \mid y) f_{true}(y) dy$$

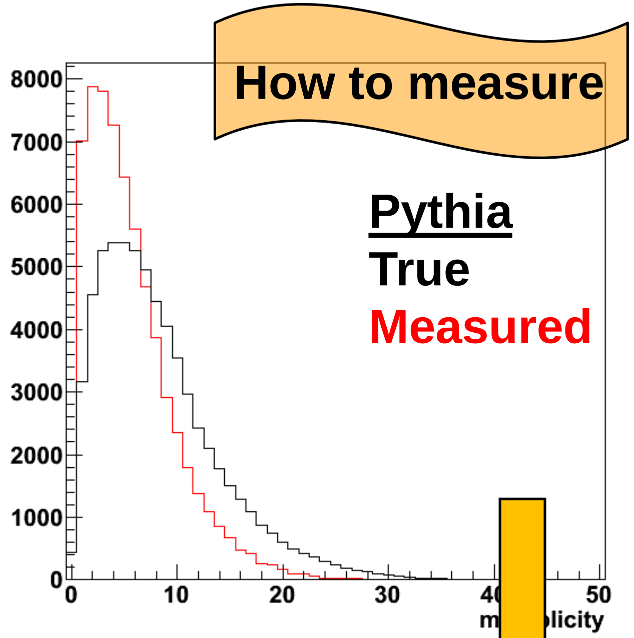
$$M = RT$$

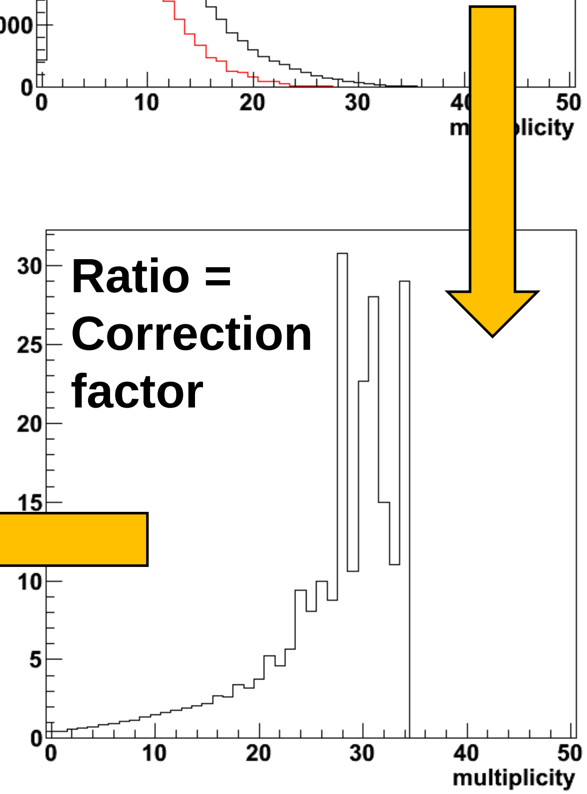
$$R^{-1} M = T$$

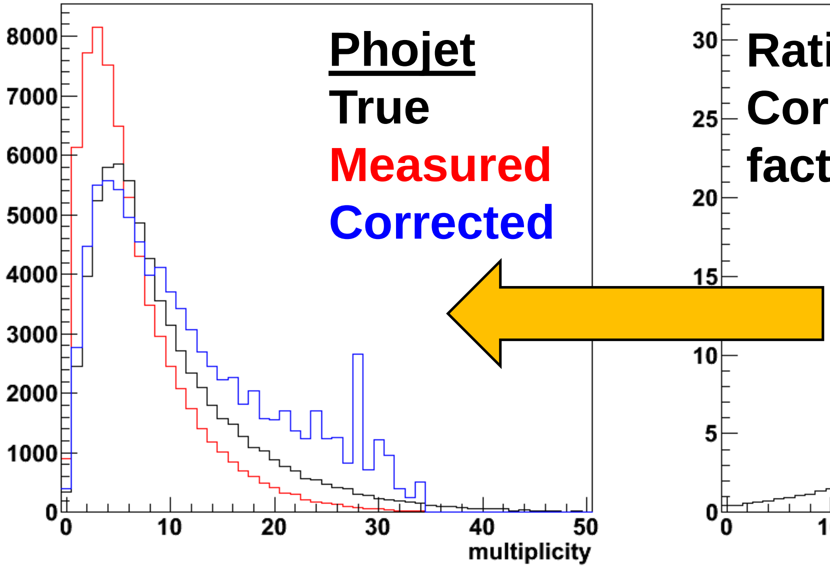
$$M = RT + BG$$

Why is it needed?

- Many analyses correct bin by bin
  – Choose binning appropriate for analysis
  – One correction factor per bin
- Correct when
  – there is only a negligible amount of bin migration
  – distributions are not steeply falling
- Incorrect when
  – there is significant bin migration
  – distributions fall steeply
  – MC does not describe the data
- Example
  – Bin by bin correction factor from Pythia to correct Phojet sample
  → Significant deviation



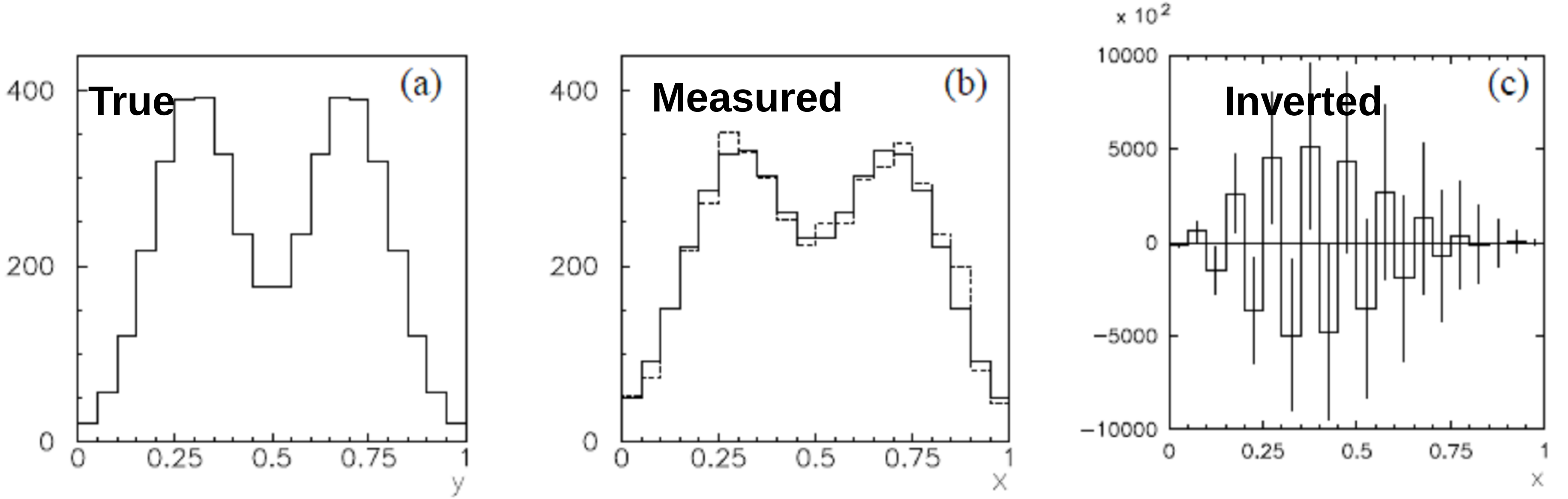




Why is it difficult?

How to measure

- Easiest approach: matrix inversion $R^{-1}M = T$
- If bin size smaller than resolution
  - Large off diagonal elements in R^{-1}
  - Negative correlations between neighboring bins
- Inverted solution
  - Suffers from large (non-physical) fluctuations
  - Can be understood → (potential) fine structure cannot be resolved by detector



from Cowan, A survey of unfolding methods for particle physics

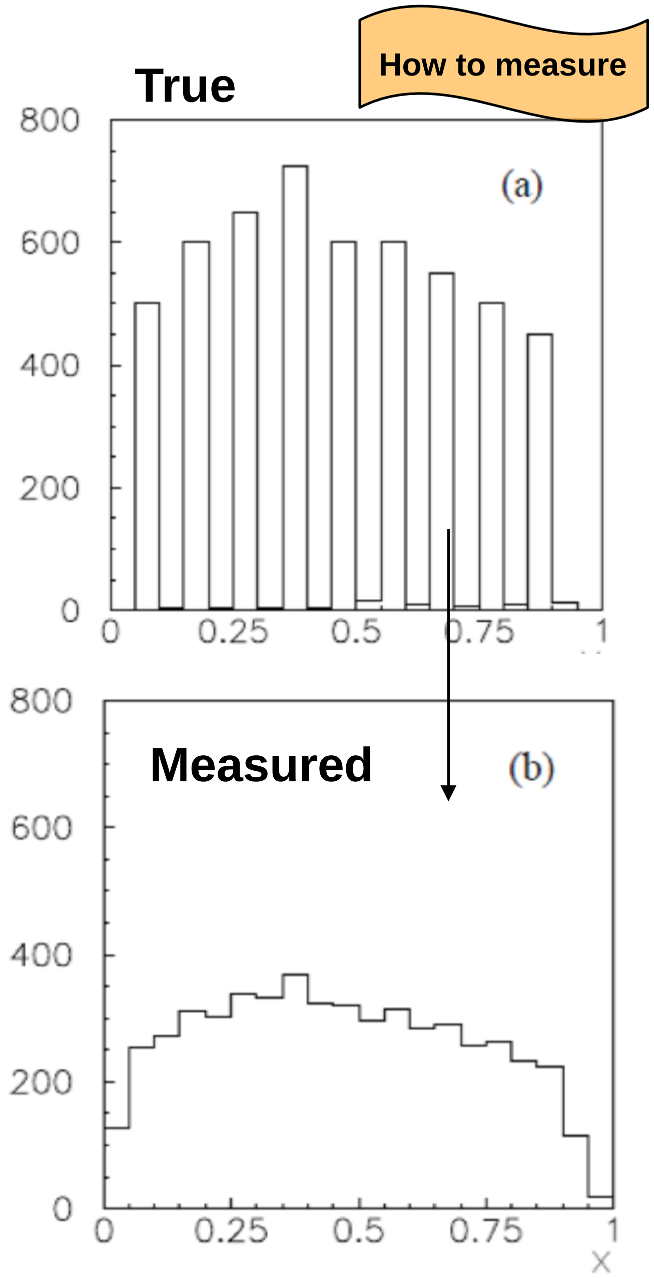
Why is it difficult? (2)

- A true distribution with a fine structure would also appear smooth in the detector

- Solution found by matrix inversion
  - Unbiased b = E[T*] – T = 0
  - Huge variance, but smallest variance of all unbiased estimators

  → Solutions with smaller variance will have a bias

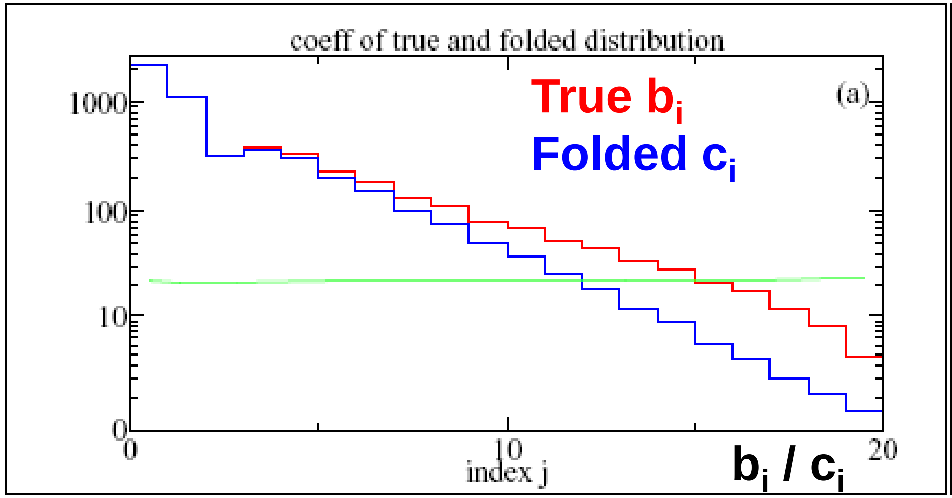
- Need to trade variance against bias
  → unfolding methods discussed today

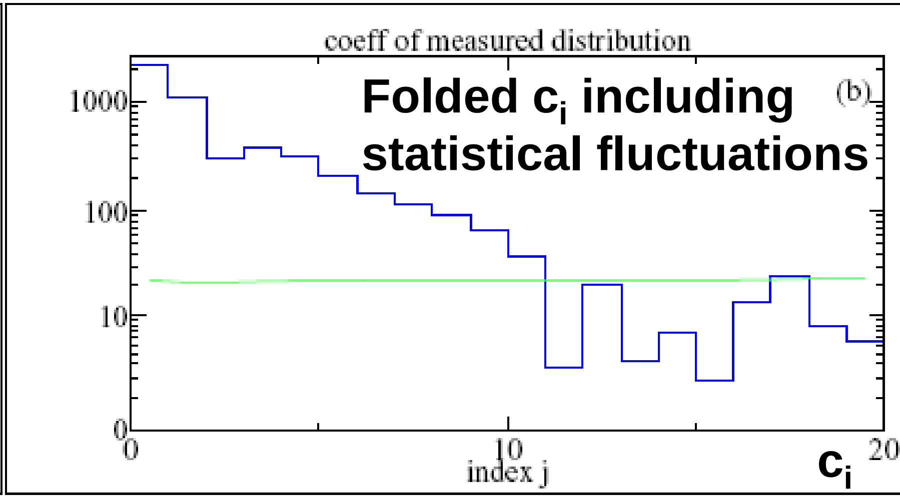


Regularized Unfolding

How to measure

- Basic equation $M = RT$
- Diagonalise response matrix $R = UDU^T$
  - D diagonal with eigenvalues of R, largest first
- Transformation matrix U with $U^T U = 1$
- Rewrite $M = UDU^T T \longrightarrow U^T M = DU^T T \qquad c = Db$
- Transformation b $\leftrightarrow$ c (folding) became multiplication with eigenvalues



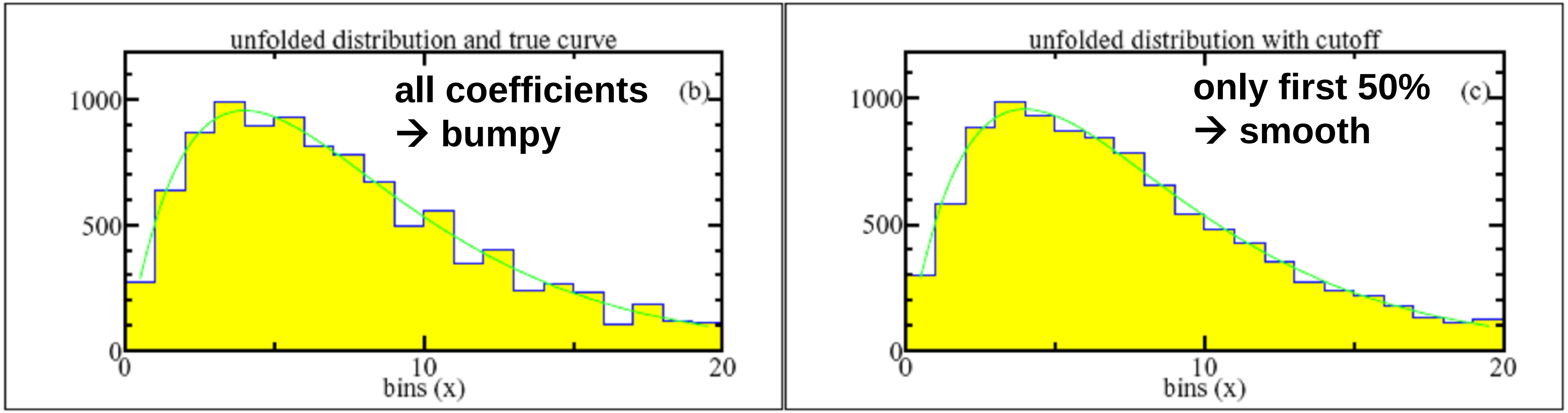


V. Blobel, hep-ex/0208022

Regularized Unfolding

How to measure

- Regularization = select which coefficients to keep



- How to select coefficients in unfolding?
  - χ^2 minimization with regularization (acts like a smooth cut-off)
  - Iterative Bayesian unfolding with limited number of iterations
    - Small eigenvalues converge slower than larger ones!

V. Blobel hep-ex/0208022

χ^2-Minimization with Regularization

How to measure

- Find the spectrum by minimizing a χ^2 function

$$\chi^2(T^*) = \underbrace{\sum_m \left(\frac{M_m^* - \sum_t R_{mt} T_t^*}{e_m} \right)^2}_{\text{“Typical” } \chi^2 \text{ term}} + \underbrace{\beta R(T^*)}_{\text{regularization term}}$$

- $R(T^*)$ only depends on unfolded guess T^*
- Weight β balances the two terms
- Without regularization term, same result as found by matrix inversion
  - One can show that the solutions are equivalent

V. Blobel, Yellow report, 1984

Regularization

How to measure

- Simple functional form which smoothens result
  - Don't add information through this term = Don't impose how it should look like
  - E.g. if you look for an exponential, don't regularize with an exponential

$$R(T) = \sum_t (a_t)^2$$

$$a_t = \frac{T_t'}{\sqrt{T_t}} = \frac{T_t - T_{t-1}}{\sqrt{T_t}}$$ **prefer constant**

$$a_t = \frac{T_t''}{\sqrt{T_t}} = \frac{T_{t-1} + 2T_t - T_{t+1}}{\sqrt{T_t}}$$ **prefer linear least curvature**

$$a_t = \frac{\hat{T}_t''}{\sqrt{\hat{T}_t}} \qquad \hat{T}_t = \ln T_t$$ **prefer exp**

- Weight parameter β needs to be tuned

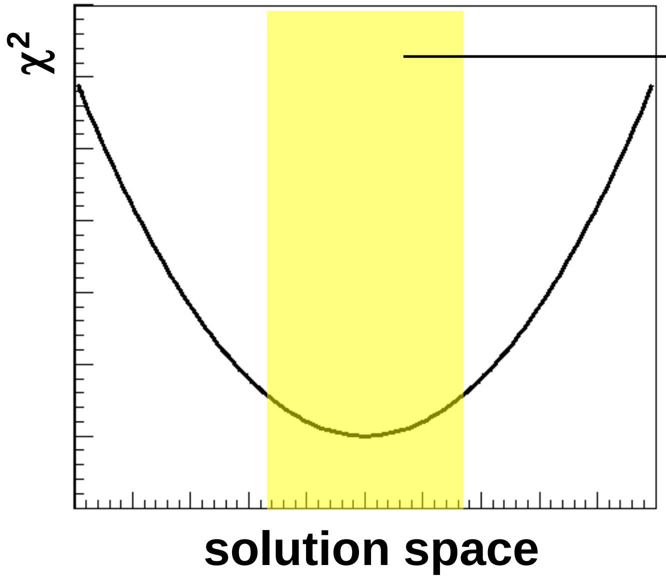
$$R(T) = \sum_t T_t \ln \frac{T_t}{\varepsilon_t}$$ **reduced cross-entropy**

NB: Regularizations based on derivatives can be implemented as matrix operation → optimization

χ^2-Minimization with Regularization (2)

How to measure

- Conceptually, instead of choosing the solution with the smallest χ^2
  - one accepts a higher χ^2
  - so that the result is smooth



choose the most smooth solution in a window defined by $\chi^2 < \chi^2_{min} + \Delta\chi^2$

Residuals

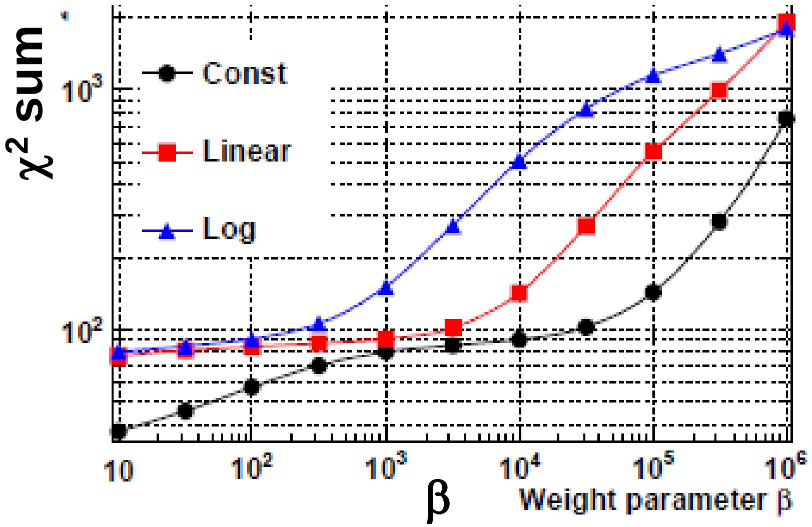
How to measure

- Residuals assess if unfolded distribution reproduces measurement
  - First part of the χ^2 function (→ normalized residuals)

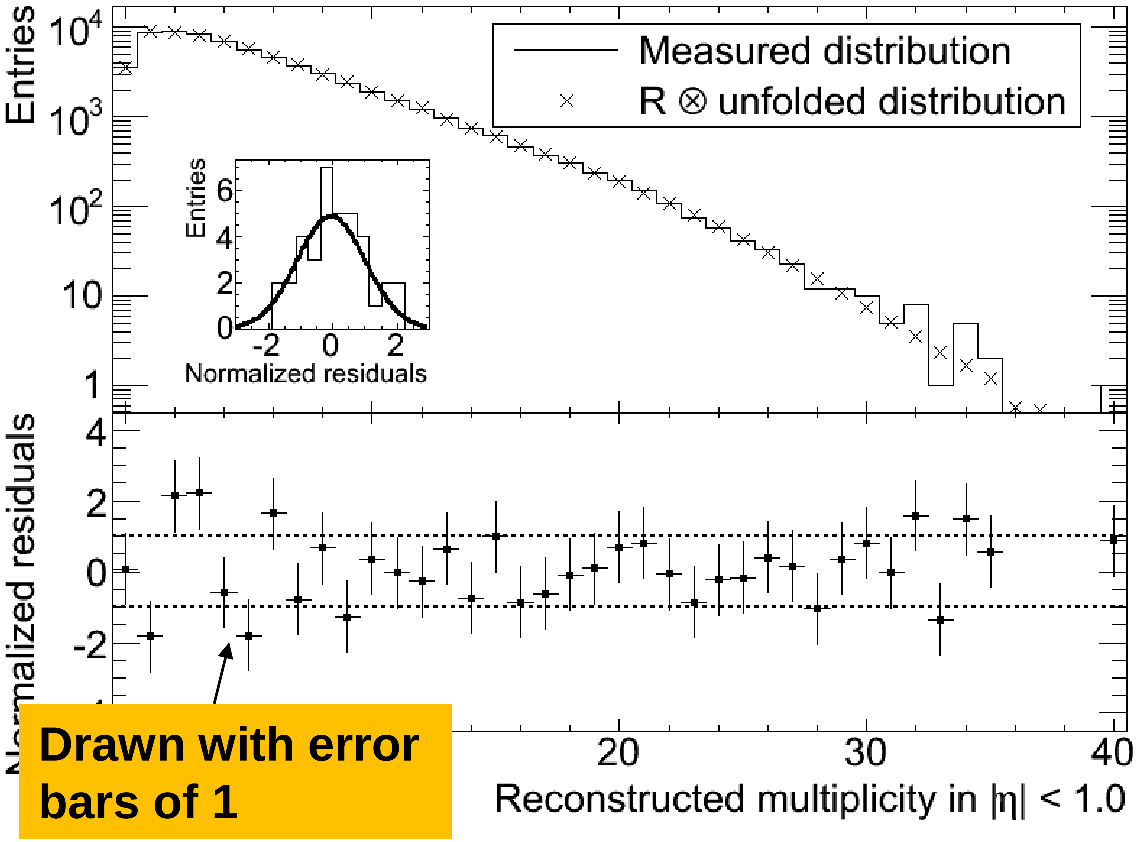
$$\mathrm{Res}_m = \frac{M^*_m - \sum_t R_{mt} T^*_t}{e_m}$$

  - Should be a Gaussian with σ of 1
- χ^2/ndf helps to choose β

$$\chi^2 = \sum_m \mathrm{Res}_m^{\ 2}$$



ndf here about 100



Drawn with error bars of 1

Choosing β: Bias

How to measure

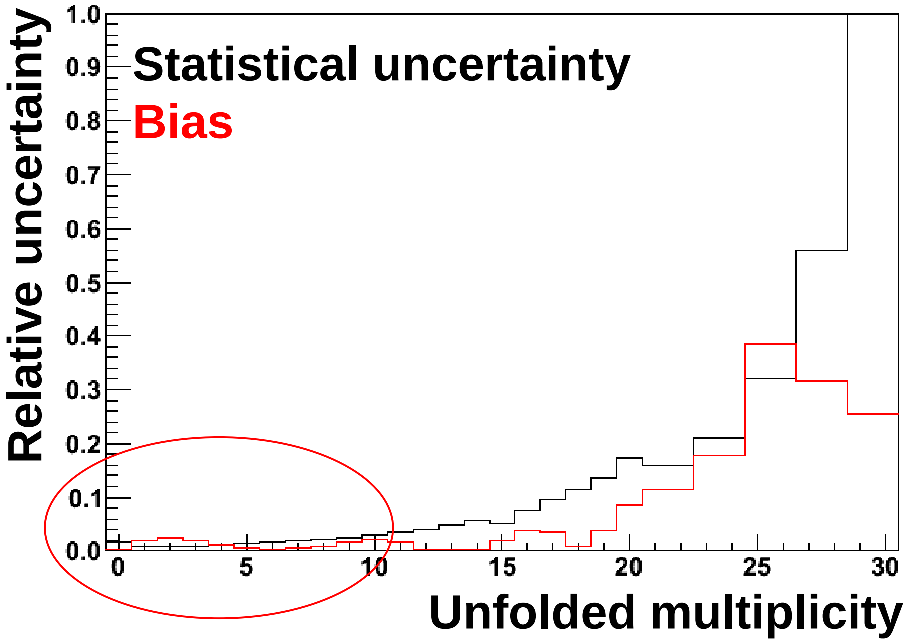
- Once found a good β, check bias

$$b_t = \sum_m \frac{\partial T_t^*}{\partial M_m^*}\left((RT^*)_m - M_m^*\right)$$

- Rule of thumb
  - Bias same or smaller than statistical uncertainty
- NB. Evaluate derivative numerically:

$$\frac{\partial T_t}{\partial M_m} = \frac{1}{6d}\left[8\left(f\left(\frac{d}{2}\right) - f\left(-\frac{d}{2}\right)\right) - \left(f(d) - f(-d)\right)\right]$$

$$f(x) = T_t(M \mid M_m = M_m + x\sqrt{M_m})$$



How to measure

Bayes‘ Theorem

- Bayes‘ theorem relates
  - the conditional probabilities
    - P(A|B) „A given B“ and
    - P(B|A) „B given A“
  - the marginal probabilities P(A) and P(B)
  - of events A and B

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

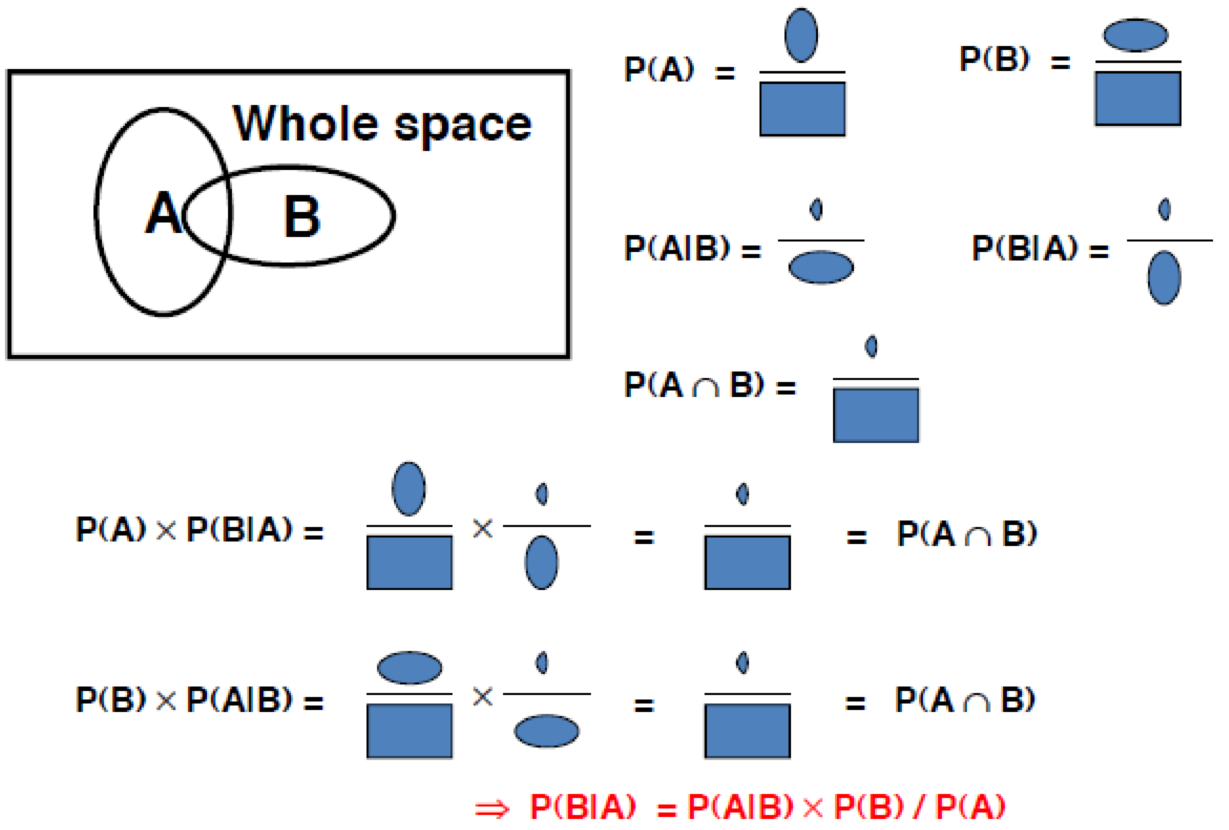


Figure: Bob Cousins

Iterative Bayesian Unfolding

How to measure

- Rewrite Bayes' theorem for our purposes
  - A = true event (track)
  - B = measured event (track)
- Assume a-priory distribution P, calculate smearing matrix $\tilde{R}_{tm}$

$$\tilde{R}_{tm} = \frac{R_{mt} P_t}{\sum_{t'} R_{mt'} P_{t'}} \qquad U_t = \sum_m \tilde{R}_{tm} M_m$$

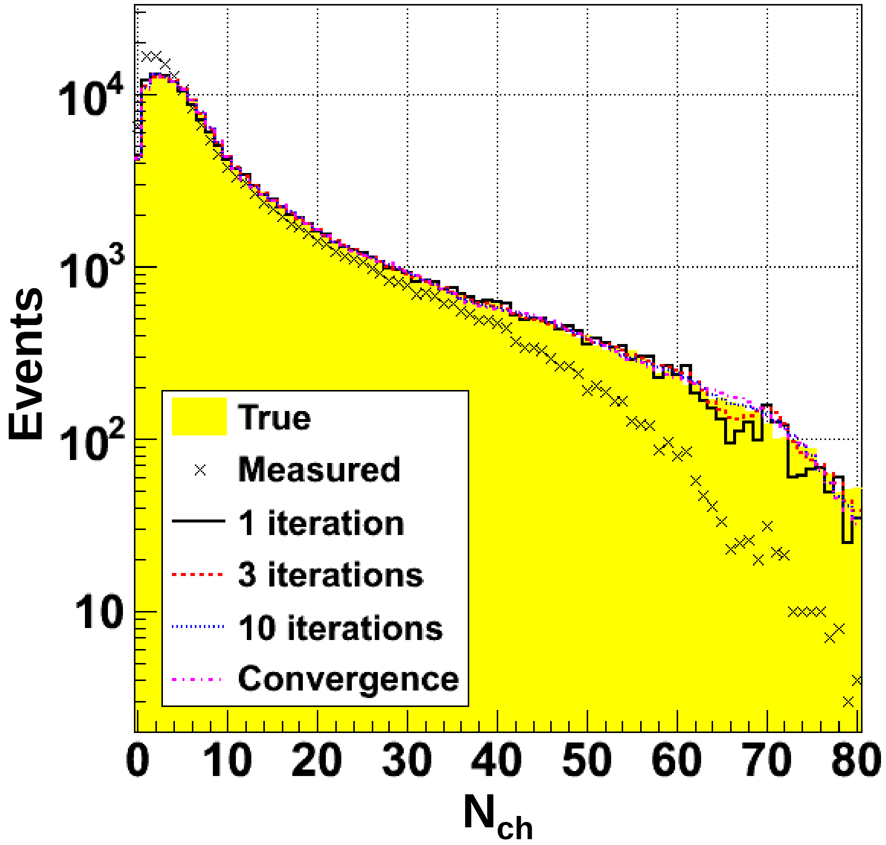
- Proceed iteratively
  - Choose prior distribution P
  - Calculate $\tilde{R}_{tm}$ and then U_t
  - Optional: apply smoothing
  - Replace P by U, iterate
- Limited number of iterations provides implicit regularization

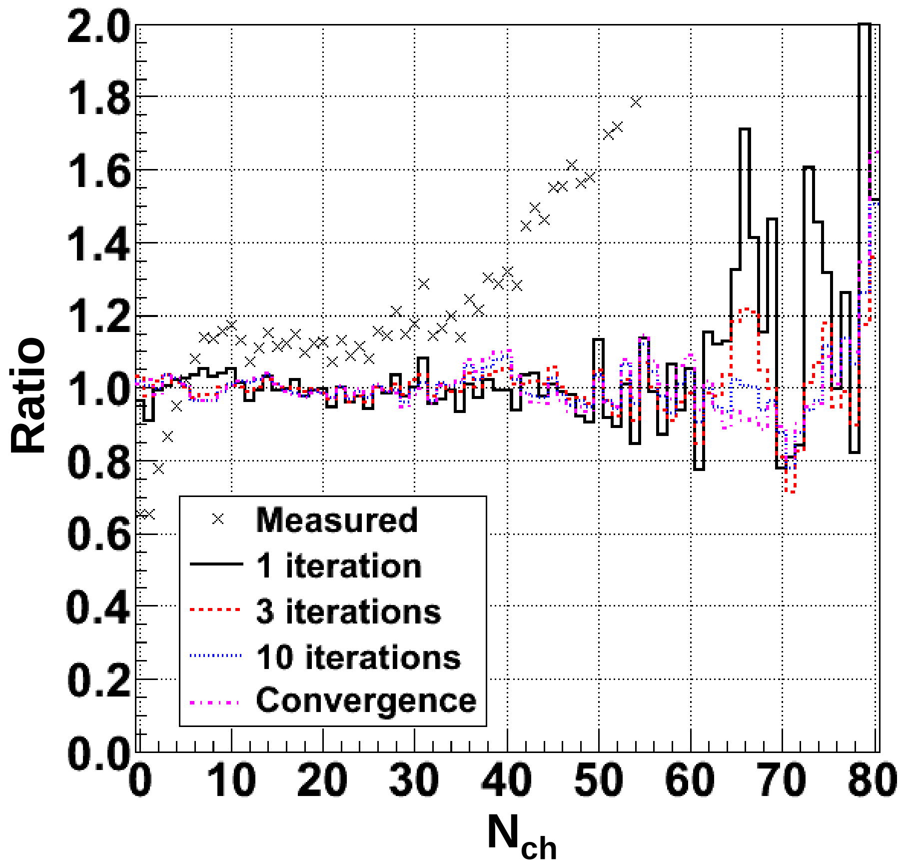
Optional Smoothing

$$\hat{U}_t = (1-\alpha) U_t + \frac{\alpha}{3}(U_{t-1} + U_t + U_{t+1})$$

Nucl.Instrum.Meth.A362:487-498,1995
Blobel, hep-ex/0208022

Example of Unfolding using Bayesian Method





already close to input distribution after 1 (!) iteration

Summary
Multiplicity Distributions

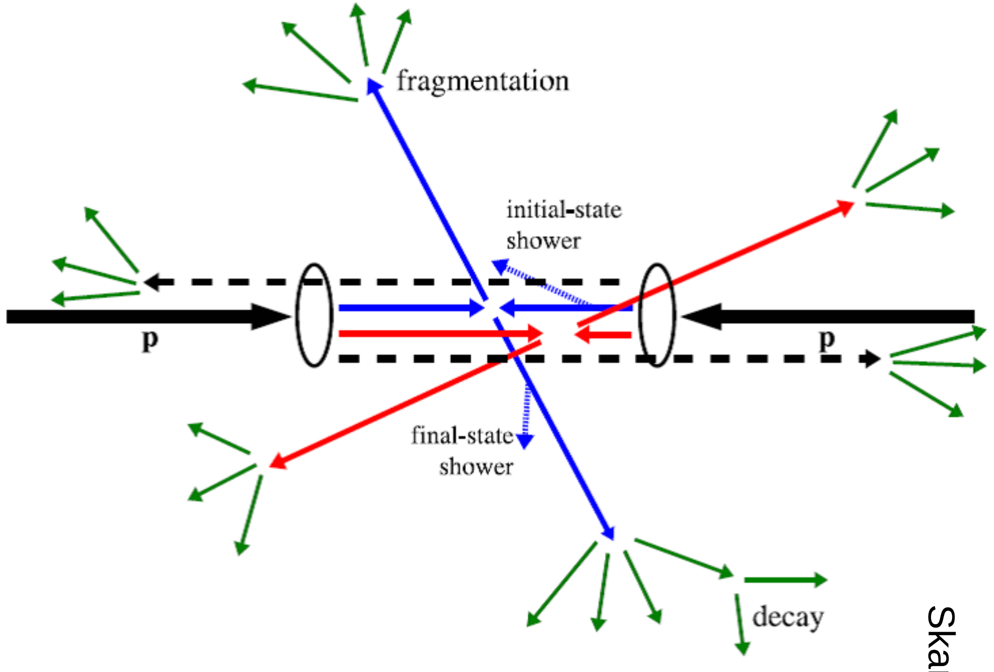
- Multiplicity distribution among basic simple observables
- Experimental unfolding procedure challenging

- Multiplicity distribution of events with different number of parton interactions looks very different
- Tail of distribution populated by events with large MPI activity
- But: measurement of multiplicity distribution for specific number of parton interactions not feasible (to date…)

Underlying Event

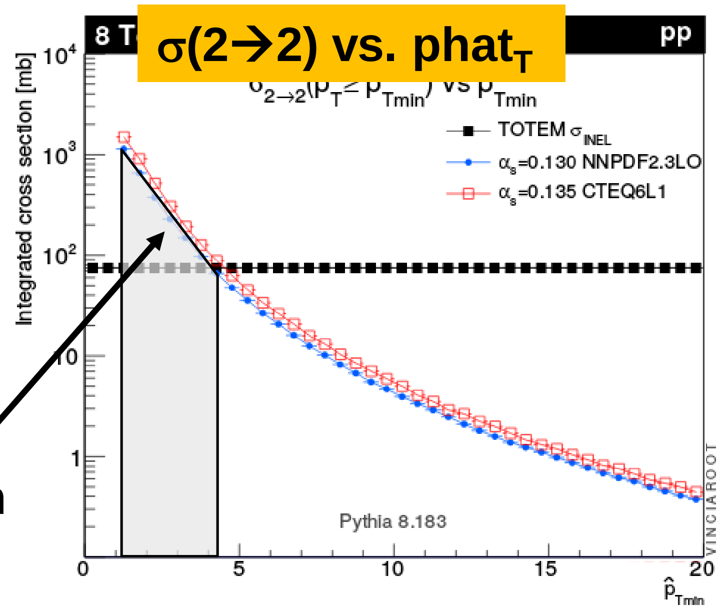
Underlying Event

- What is the underlying event (UE)?
  - *Anything* below the hardest scattering



- Due to steeply falling cross-section
  - Most events have soft component
  - If there is a hard parton scattering, there are additional soft parton interactions

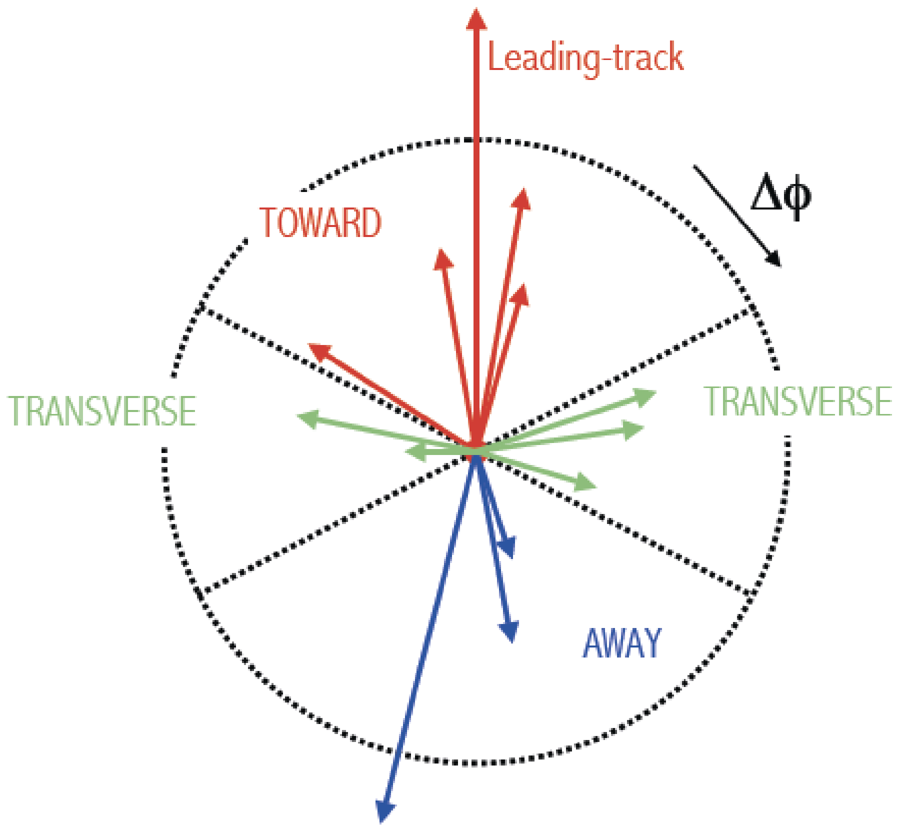
Most events have (more than one) “soft” parton scattering



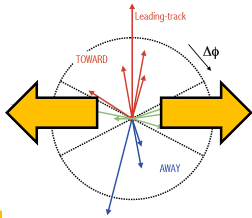
Skands, Carrazza, Rojo, arXiv:1404.5630

Underlying Event (2)

- Find hardest object
  - Charged track, jet, Z, …
- Study distinct azimuthal regions wrt object
  - Transverse ($1/3\pi < |\Delta\varphi| < 2/3\pi$) = UE
    - May be split into MIN and MAX region
  - Towards ($|\Delta\varphi| < 1/3\pi$)
  - Back-to-back ($|\Delta\varphi| > 2/3\pi$)
- Typical observables
  - Number density, Σp_T, σp_T



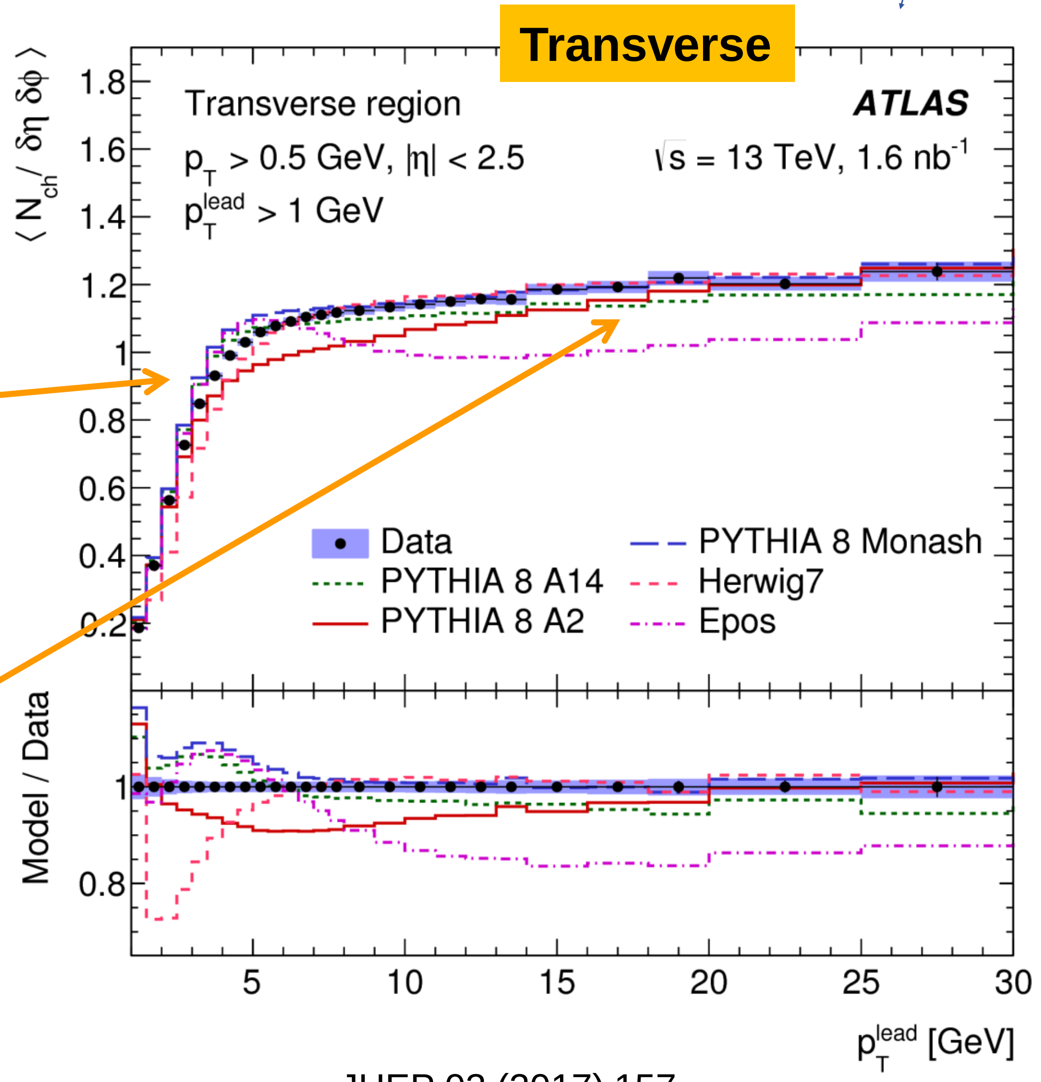
Number Density (transverse)



- Activity perpendicular to hard object

- Strong rise at low $p_{T,lead}$
  - Impact parameter dependence → MPI
  - "Trivial" selection bias

- Mild positive slope at large $p_{T,lead}$
  - Initial- and final-state radiation



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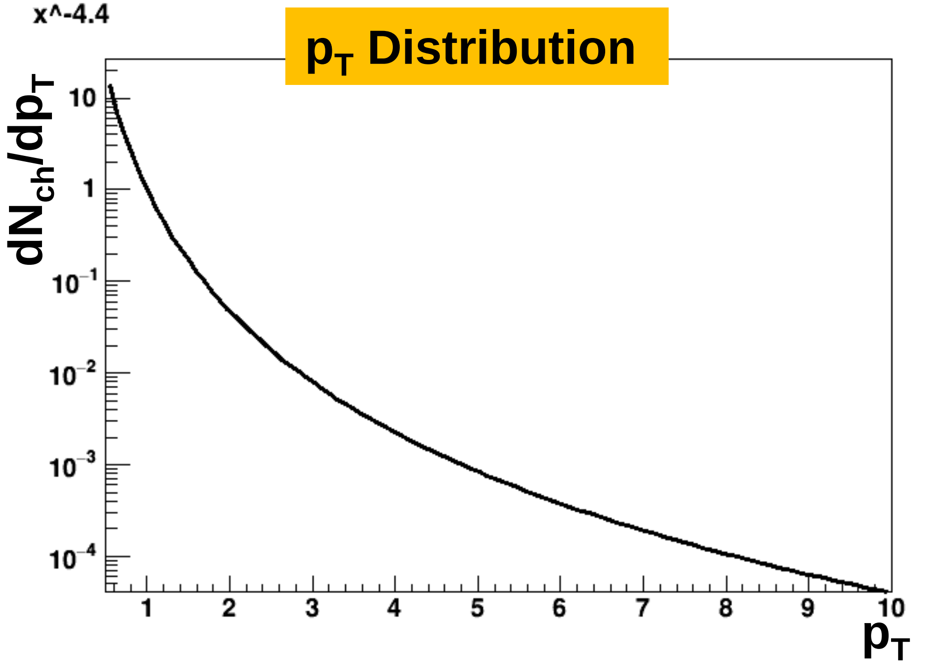
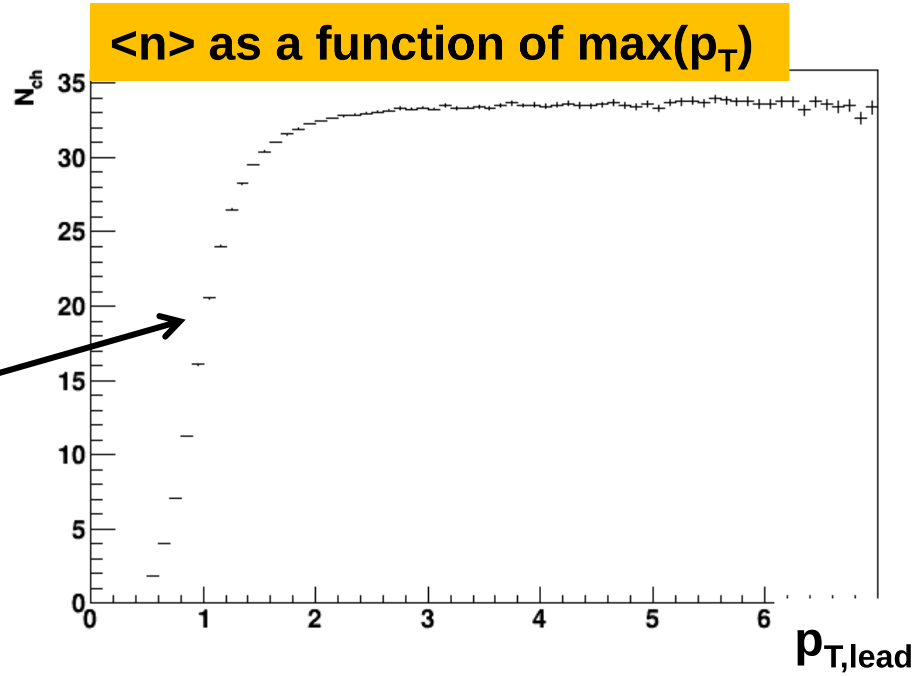
Selection Bias

- Trivial bias in distribution
  - The more particles drawn, the higher max p_T
- Can be shown with simple toy (~20 lines ROOT, see backup)
  - p_T distribution: $dN/dp_T \sim pT^{-4.4}$
  - Draw n particles from this distribution
  - Determine max(p_T)
  - Calculate <n>(max(p_T))



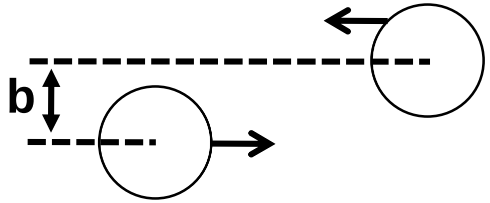


Steep increase as in observed underlying event distribution

Onset and level of plateau depends on N_{ch} distribution

Impact Parameter Dependence

- Chance for parton interactions depends on pp impact parameter



- Reminder: in pp collisions b is not directly accessible
(contrary to AA collisions)

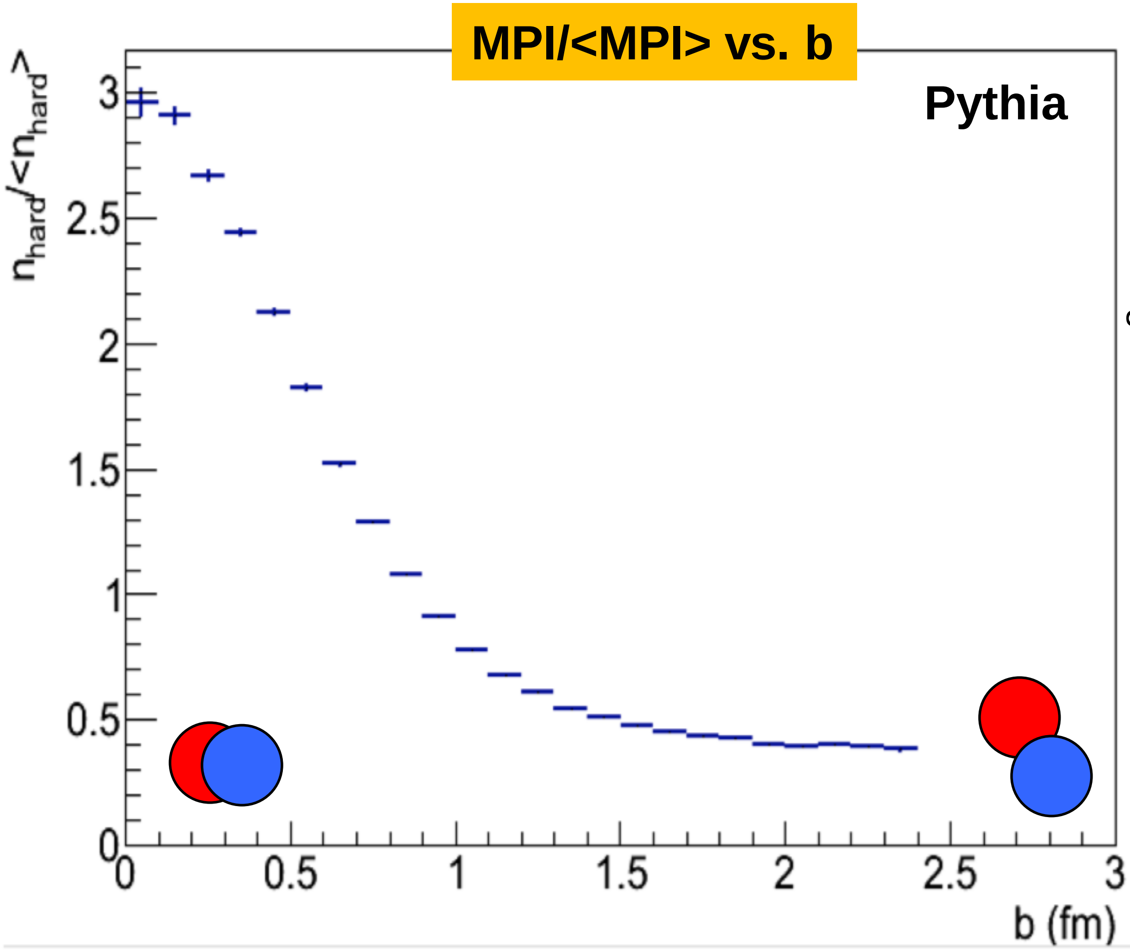
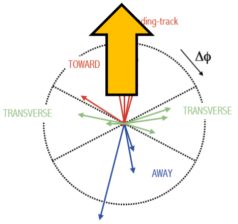
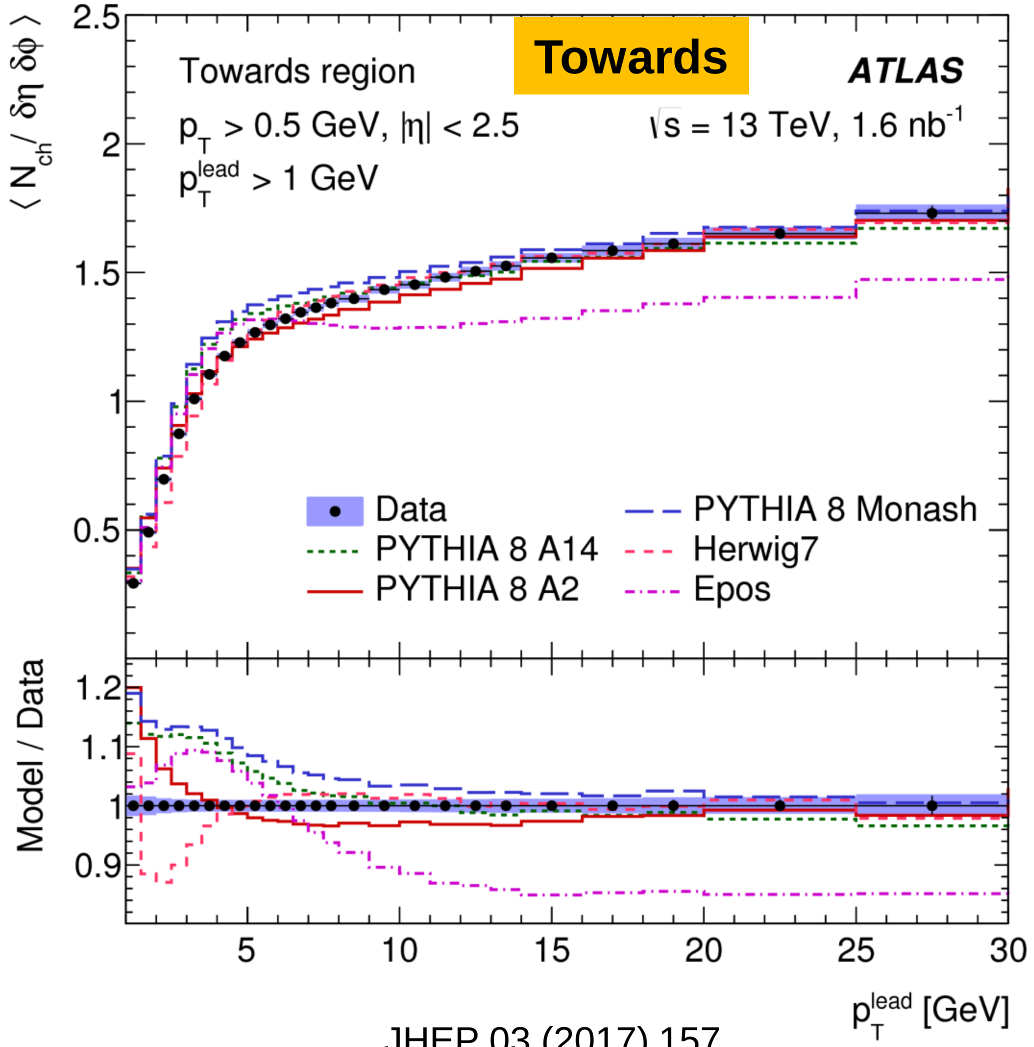


Figure: Andreas Morsch

Number Density (towards)



- Activity in direction of leading object
- Overall similar picture
  - Steep increase, then mild increase
- Larger slope at large $p_{T,lead}$ than in the transverse region
- Harder jets fragment into
  - more particles
  - leading object with higher p_T



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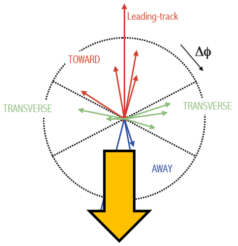
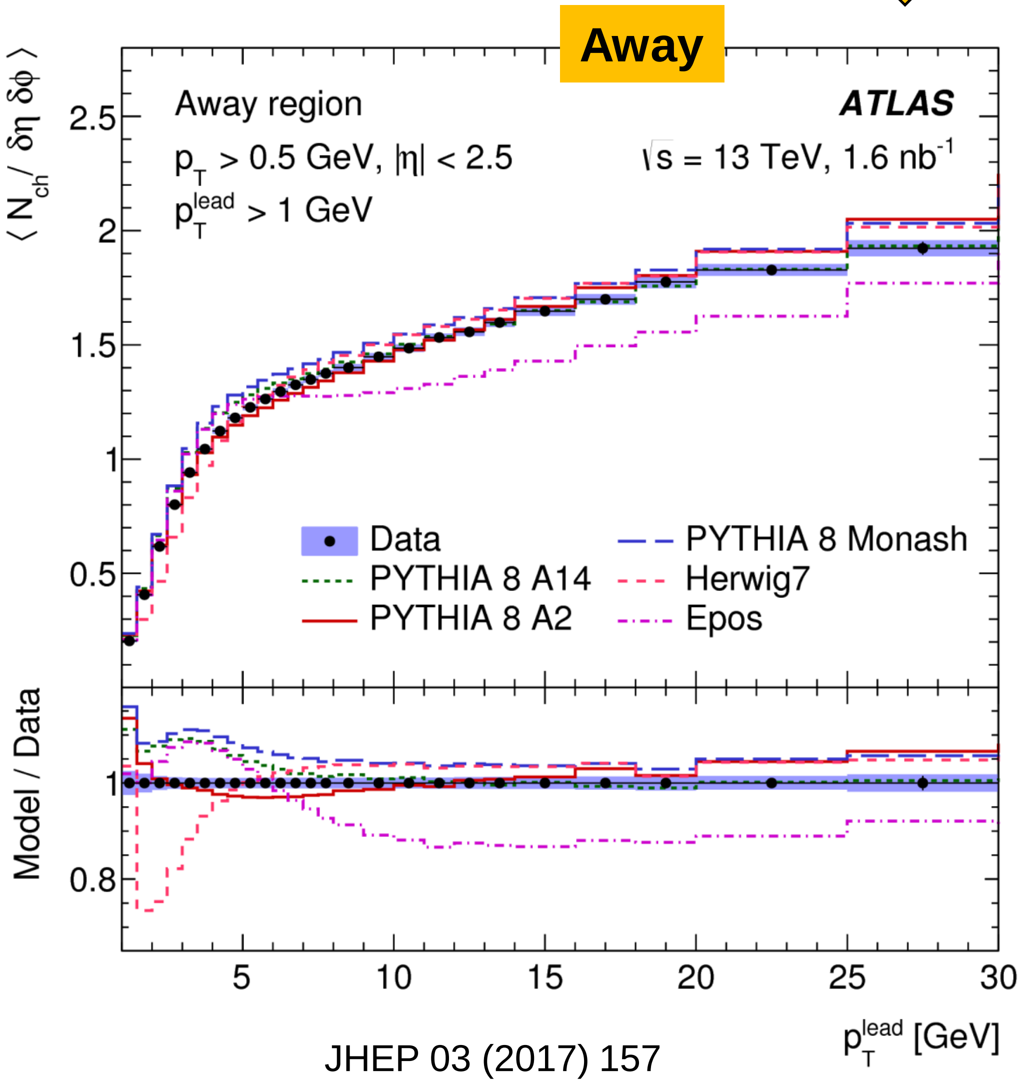
Number Density (away)



- Activity back-to-back of leading object
- Overall similar picture
  - Steep increase, then mild increase
- Similar slope at large $p_{T,lead}$ than in the towards region
- Conclusions as for towards region
  - Balancing jet has similar p_T



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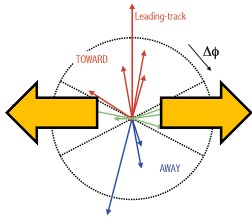
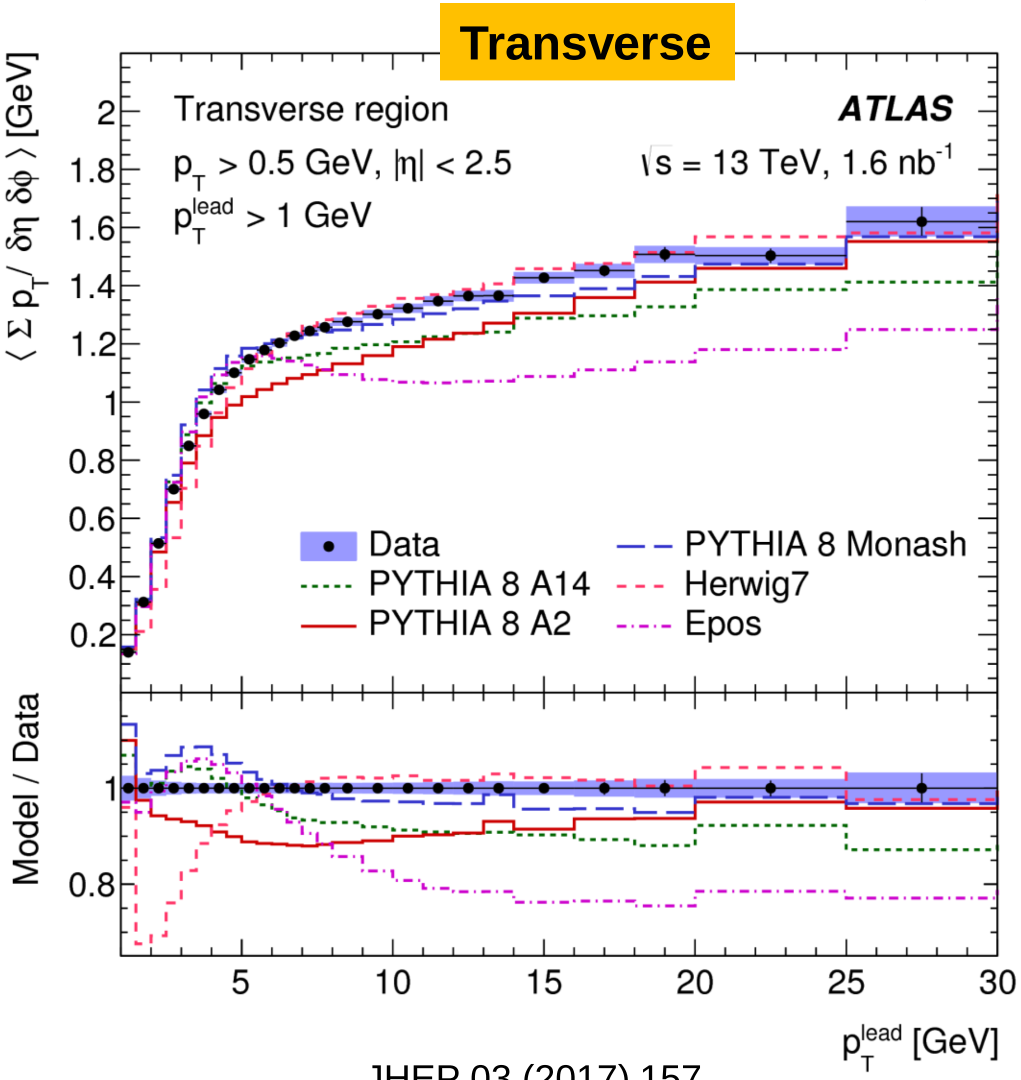
Σp_T (transverse)



- Instead of counting the particles, measure their Σp_T
- Generally similar trends
  - Watch details in comparison to N_{ch} !



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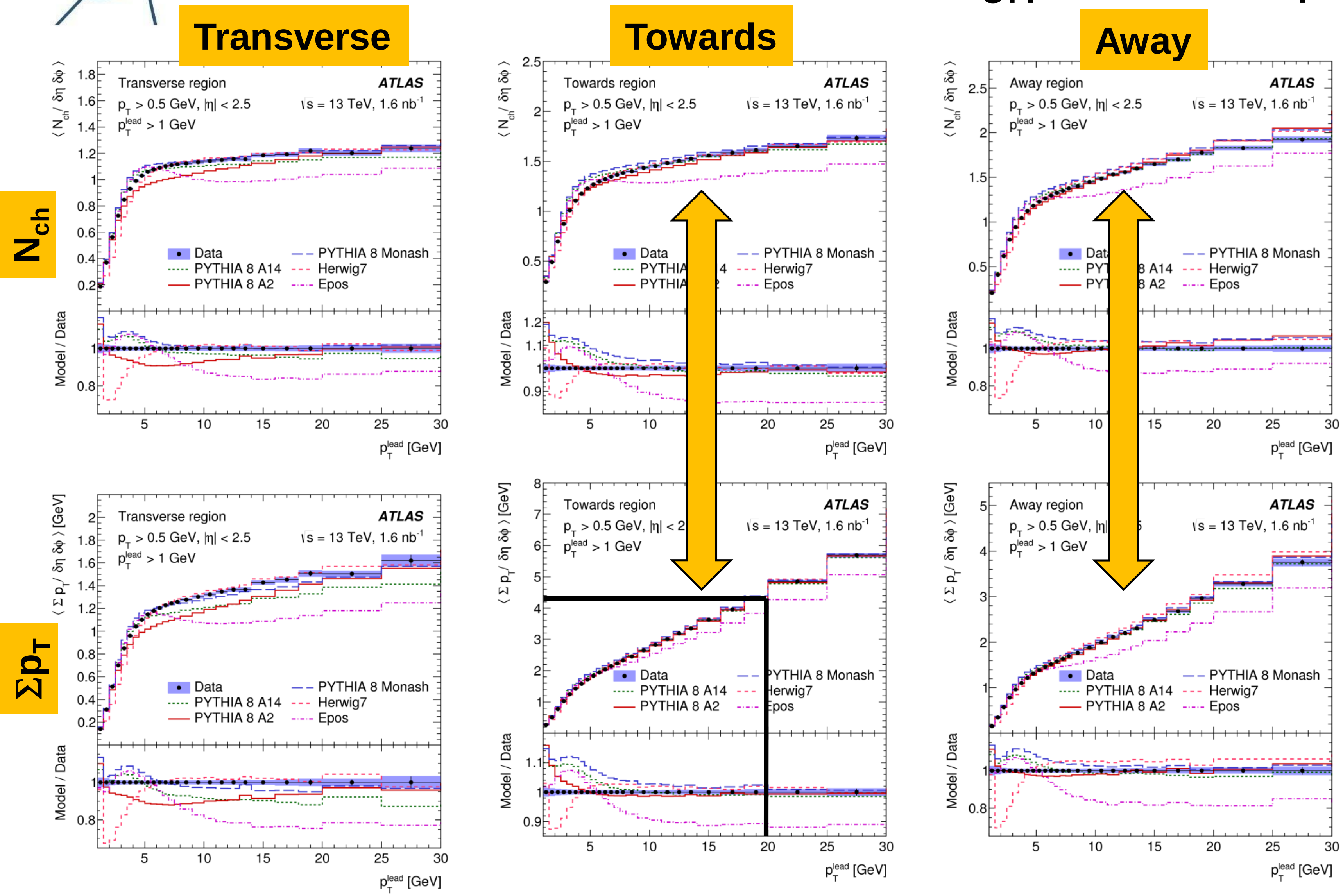
N_{ch} vs. Σp_T



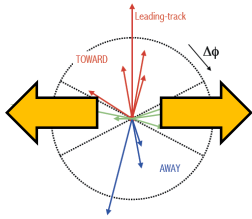
- N_{ch} and Σp_T similar for transverse region
- Differences in towards and away region
  - Σp_T closer correlated to leading p_T
  - Harder jets carry more momentum

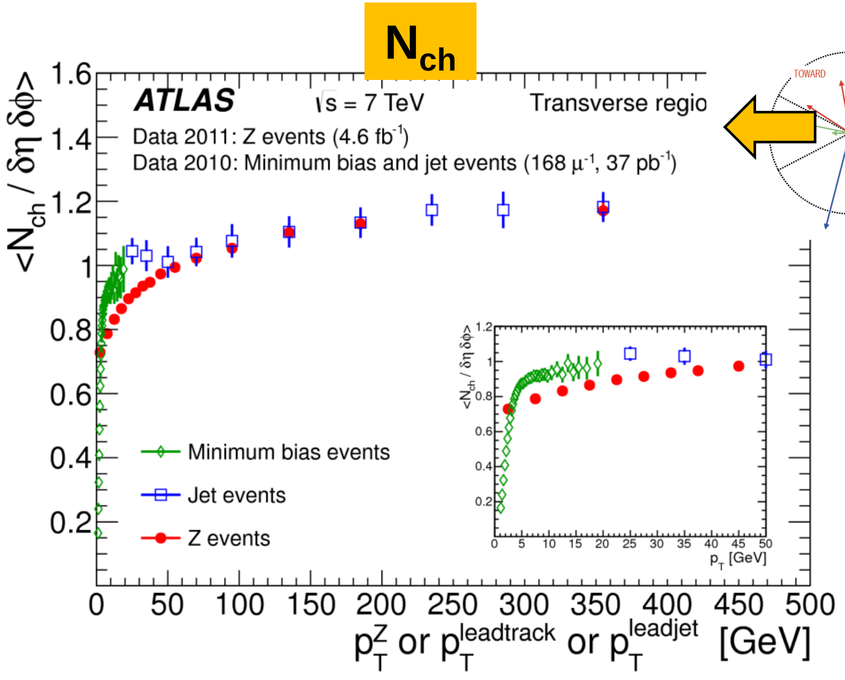
Leading object constitutes large fraction of Σp_T (only in towards region)

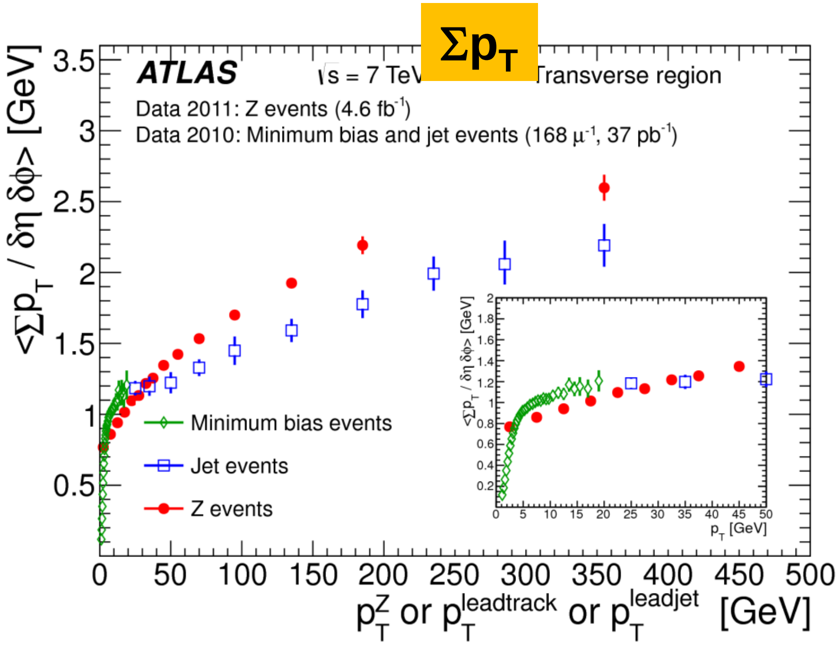
- For these plots, phase space factor $\delta\eta\delta\varphi = 2/3\pi*2.5 \sim 5.2$ → 20 GeV/c → $\Sigma p_T = 3.82$

UE vs. jets and Z

- Leading track and leading jet measurements show similar dynamics
- Leading Z boson p_T different
  - Different turn on in N_{ch}
  - Larger activity in Σp_T



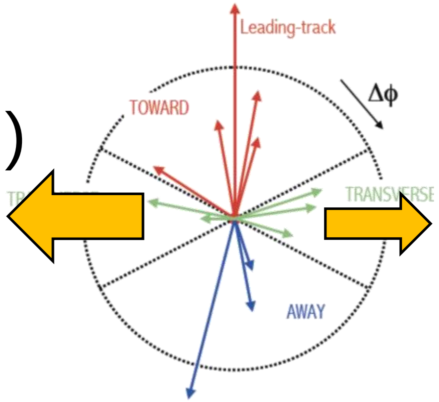


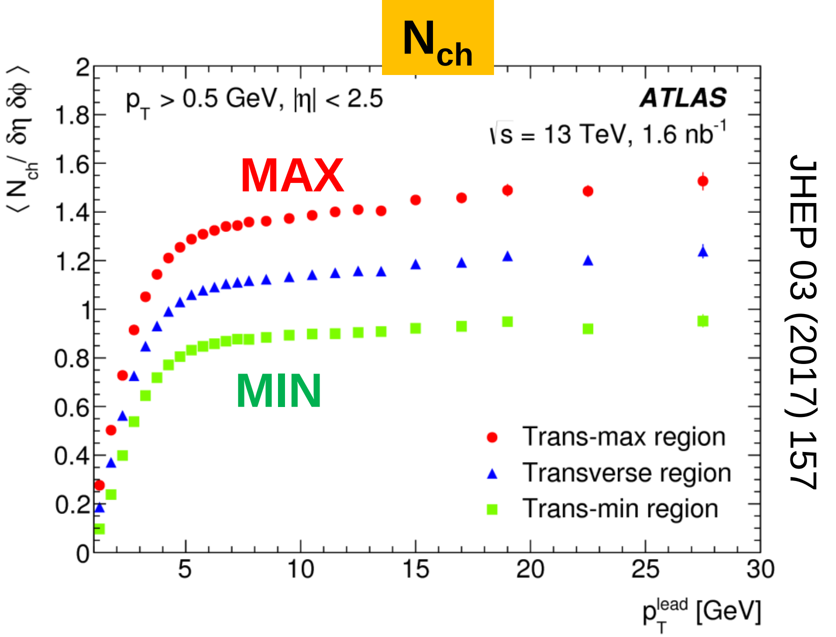


Eur. Phys. J. C (2014) 74:3195

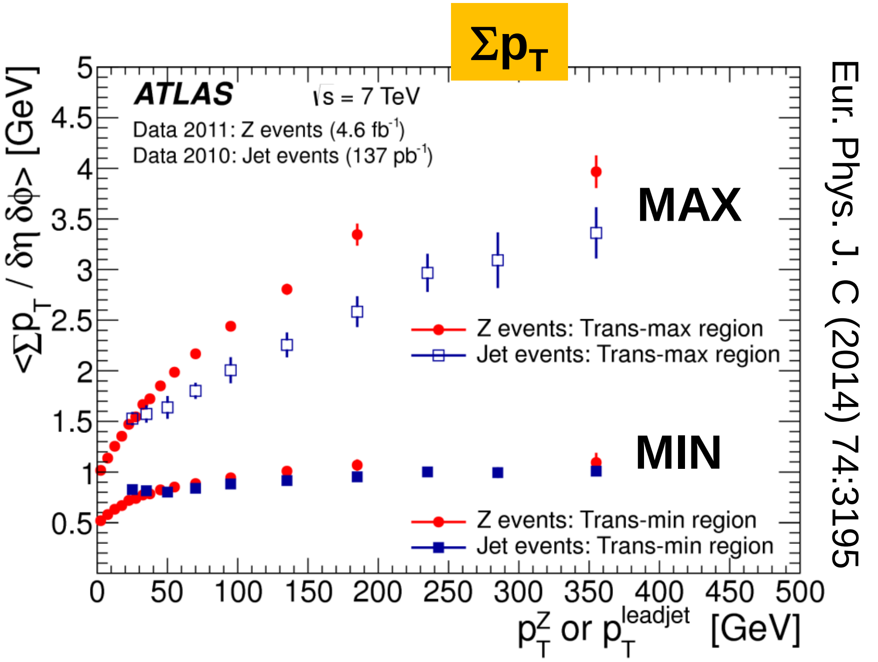
Transverse Min and Max

- Split transverse region
  - more (MAX) and less activity (MIN)
  - measured by Σp_T
  - About 20% effect

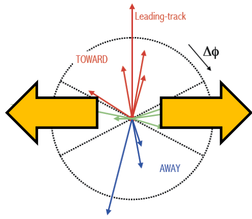




- Differences between Z and jet result vanishes in transverse MIN
  - Most sensitive to other parton interactions independent of the hard object



Dependence on p_T cut



- Results with three different low p_T thresholds
- More than 75% of the particles within $0.15 < p_T < 1$ GeV/c
- Particularly important for MC tuning

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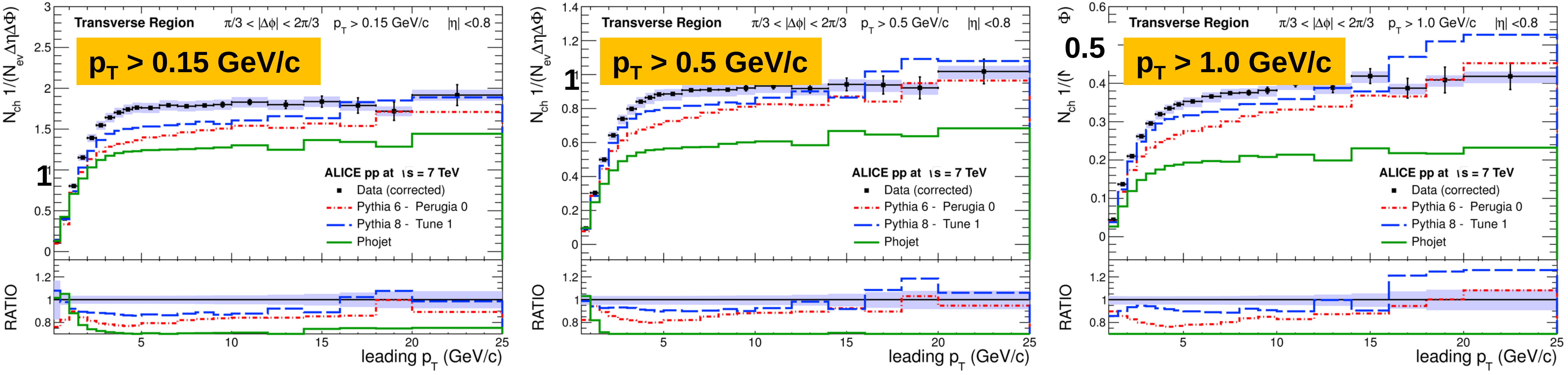
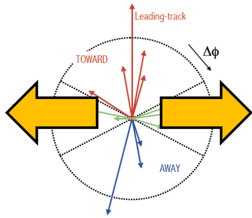
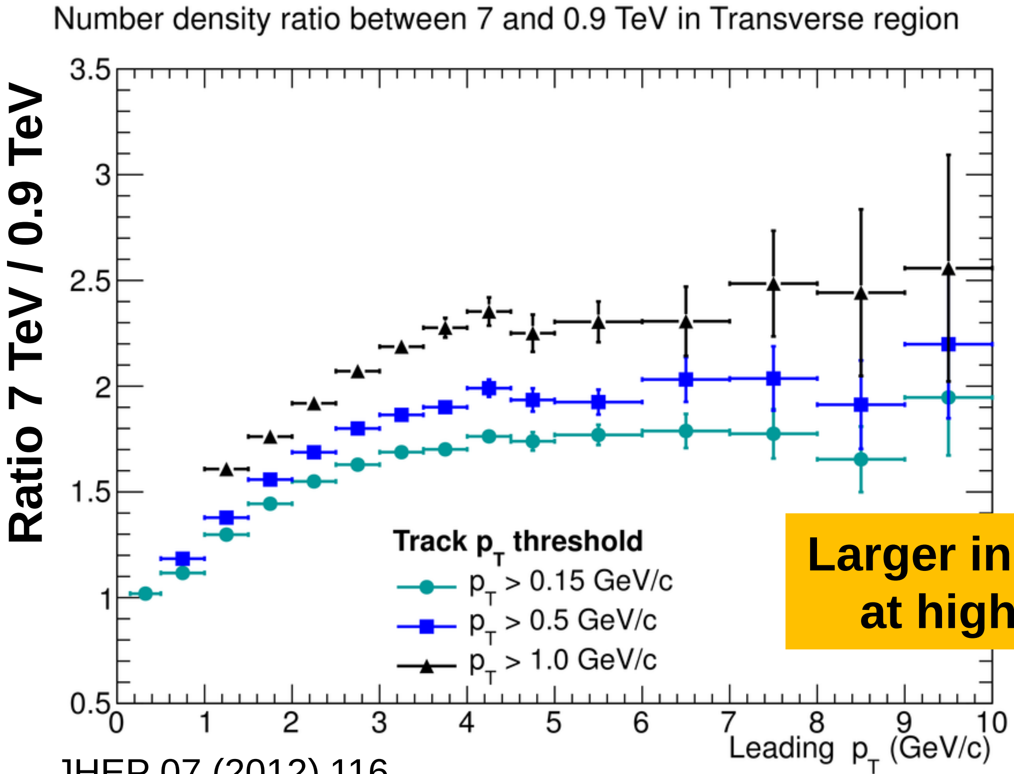


√s Dependence



- Significant increase with √s
  - As overall multiplicity



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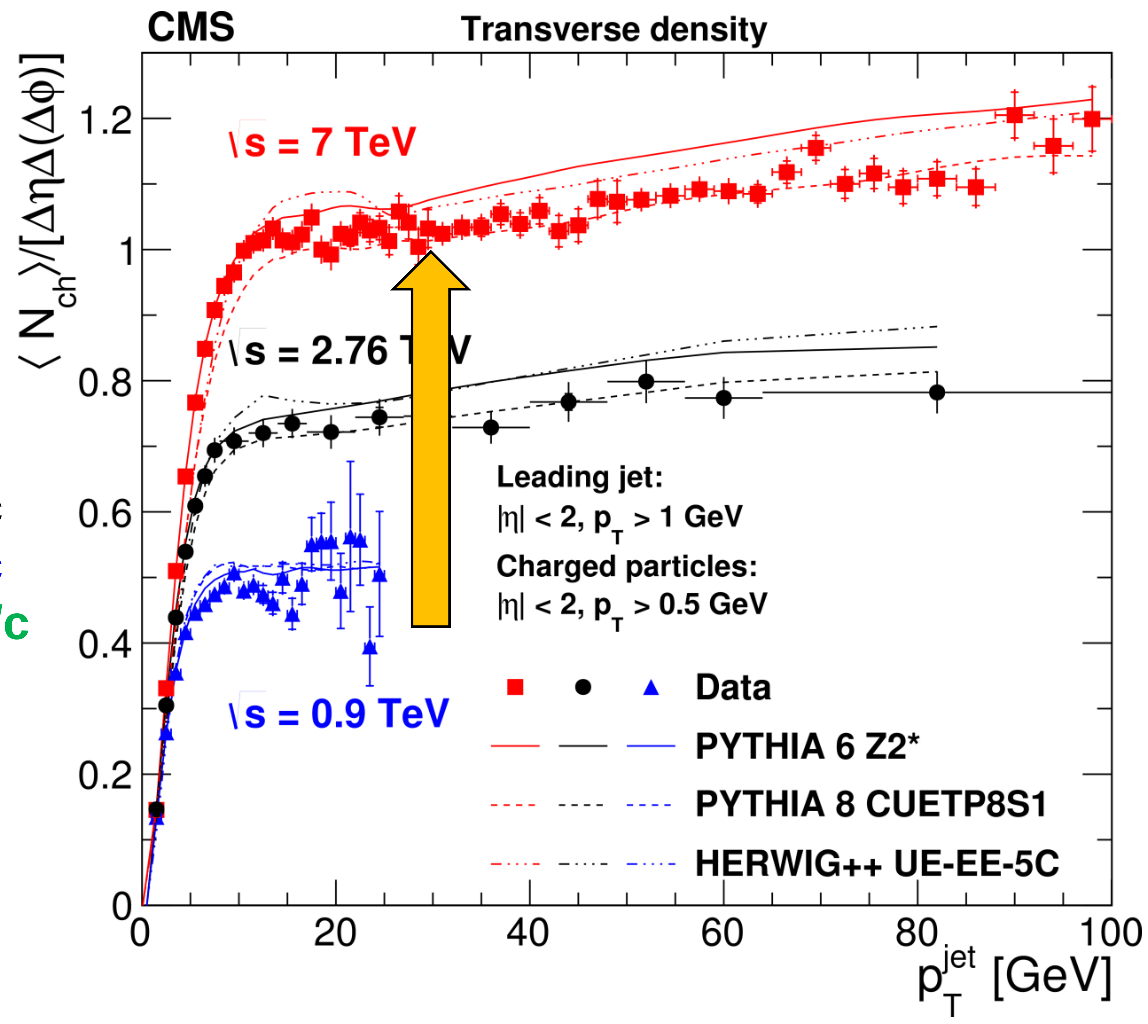
p_T > 1.0 GeV/c

p_T > 0.5 GeV/c

p_T > 0.15 GeV/c

Larger increase at higher p_T



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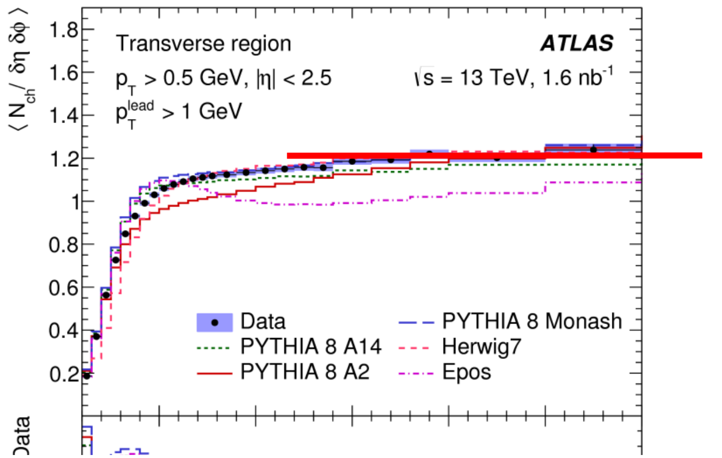
Relation of N_{ch} and UE

- Compare
  - Overall average multiplicity (of MB collisions)
  - Plateau in transverse region (the UE contribution)
- Steeper slope in UE than MB
- With increasing √s, UE grows faster than average
- Sensitive to interplay of hard process, ISR, FSR and MPI



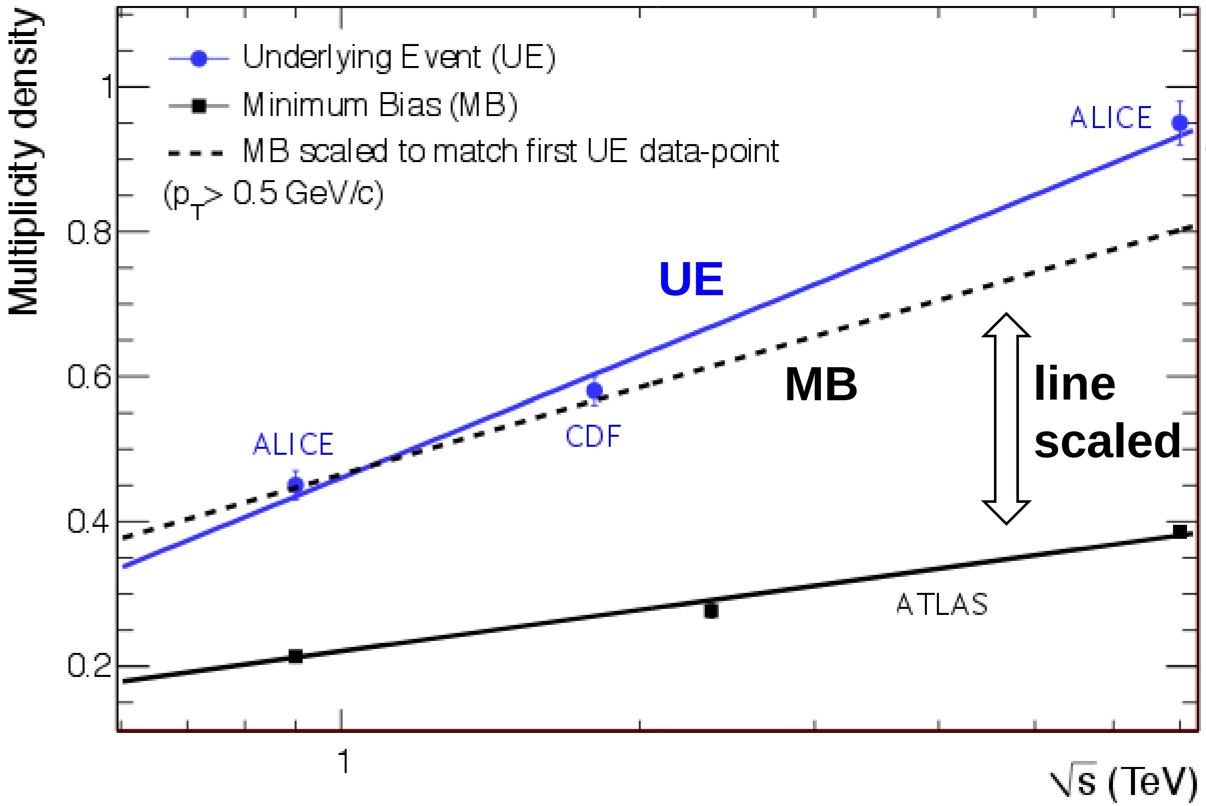
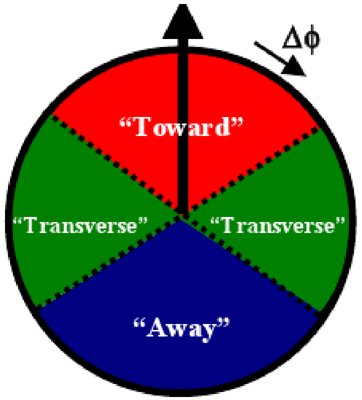


Figure: PhD thesis, Sara Vallero

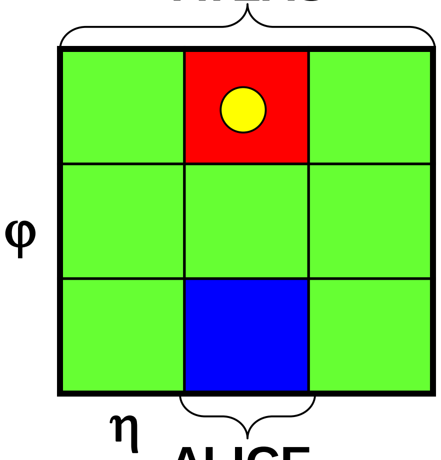
Influence of Acceptance

Acceptance ranges important!

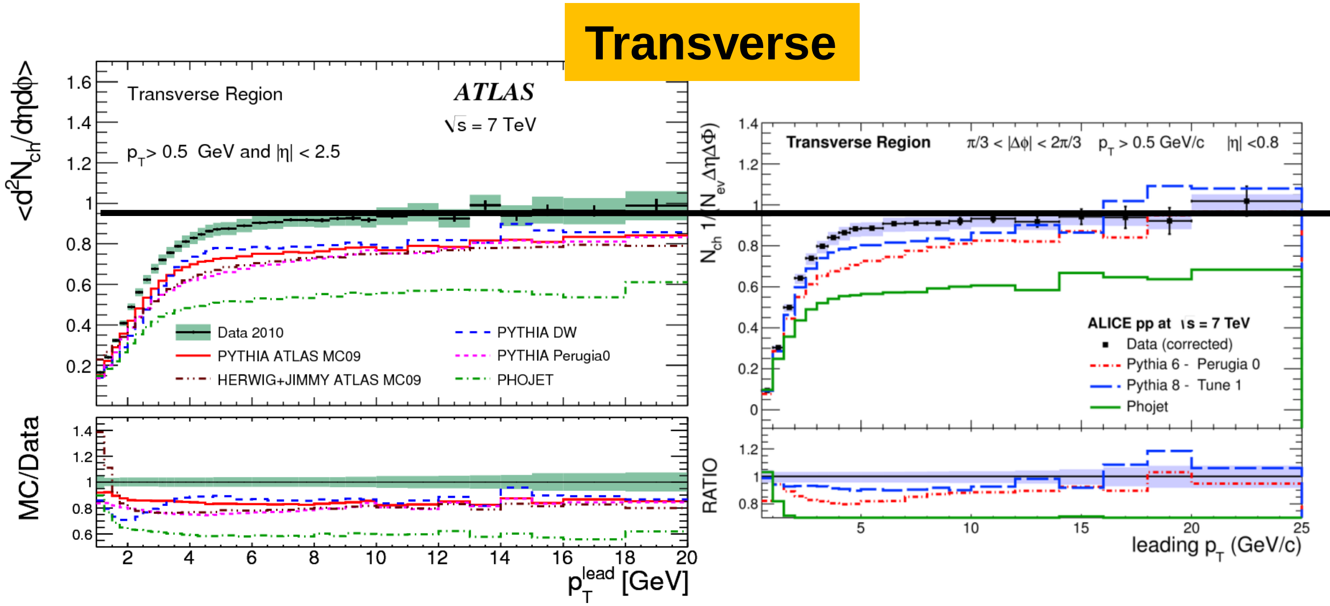
- ATLAS ($|\eta| < 2.5$) vs. ALICE ($|\eta| < 0.8$)
  - Transverse region similar
  - Large difference in towards
- Due to size of jet around leading particle

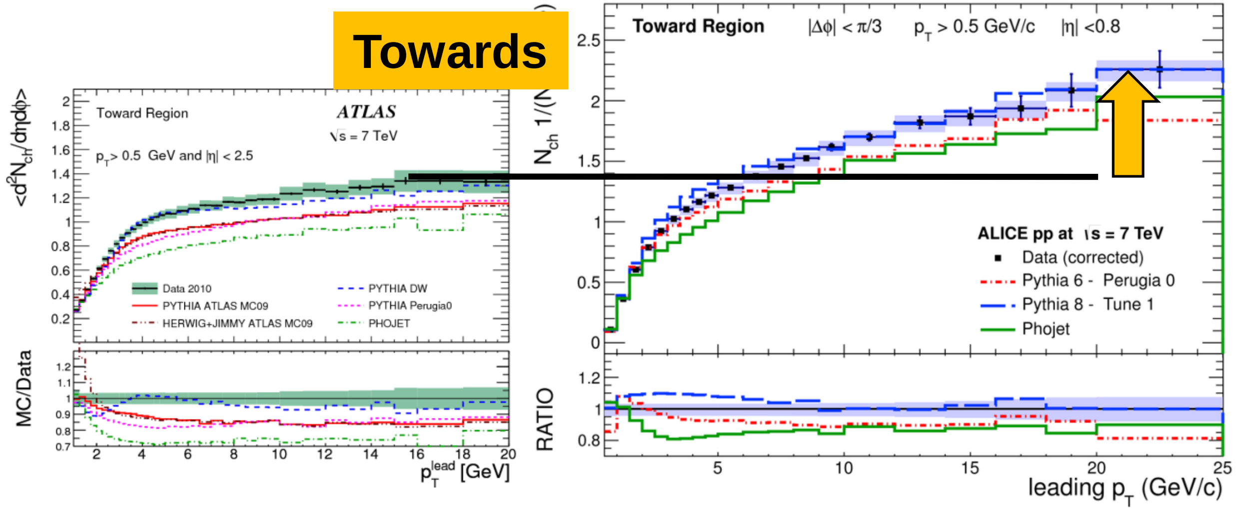


ATLAS



ALICE





- Can be checked numerically

  (1 x ALICE towards + 2 x ALICE transverse) / 3 = ATLAS towards

Corrections

How to measure

- Published underlying event distributions != raw measurement

- Let’s use this example to understand
  - which detector effects are relevant
  - how to correct for them

- You need two things: 1) brain  2) MC 
- Procedure
  - Make a list of effects which could affect your measurement (involves: previous analysis, discussion with colleagues, papers, …)
  - Test these on MC

Finding a Correction Procedure

How to measure

- Testing with MC
  - Construct your observable at many different steps
- Event level

  All Events → Triggered → With reco. vertex → Track with p_T > 0.5 GeV/c

- Track level

  MC Truth (all primaries) → MC Truth (reco. primaries) → MC Truth (reco. primaries + secondaries) → Reco. quantities (primaries + secondaries)

- Develop + apply corrections

  Corrected for secondaries → Corrected for tracking efficiency → Result

- Compare the distributions at the different levels
  - Reveals effects.
    Maybe some negligible → no correction needed
  - MC *Closure*: Do the two blue boxes agree?

Use the same sample to produce corrections and plots → closure should be exact.
Very powerful to find issues and bugs!

Strength of Detector Effects

How to measure

- Example for ALICE, pp, 7 TeV (PhD thesis, Sara Vallero)

- Event level

All Events → 90% → Triggered → 90% → With reco. vertex → 75% → Track with p_T > 0.5 GeV/c

BUT effect on observable minimal!

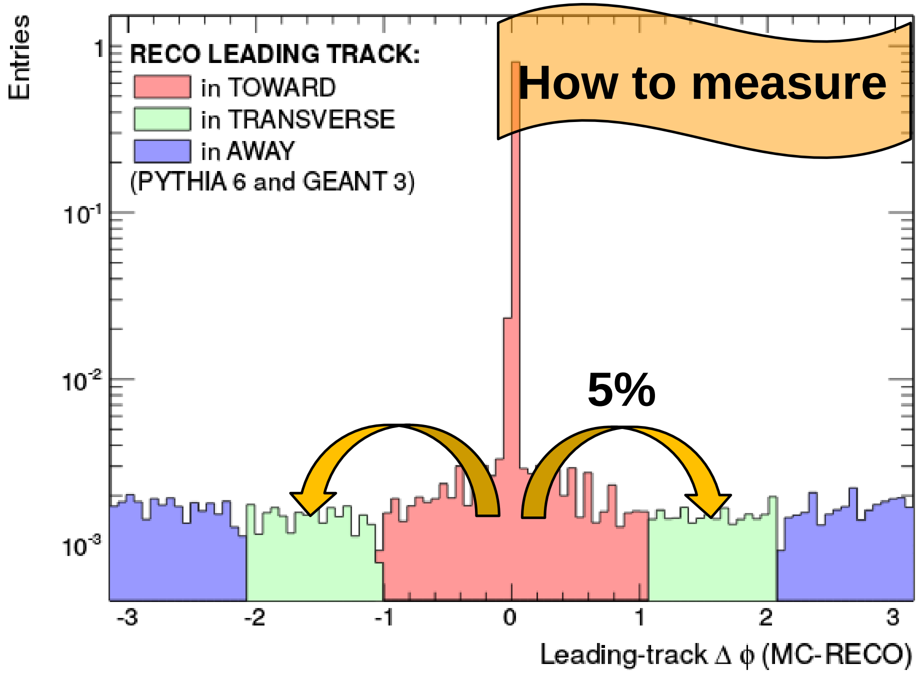
- Track level

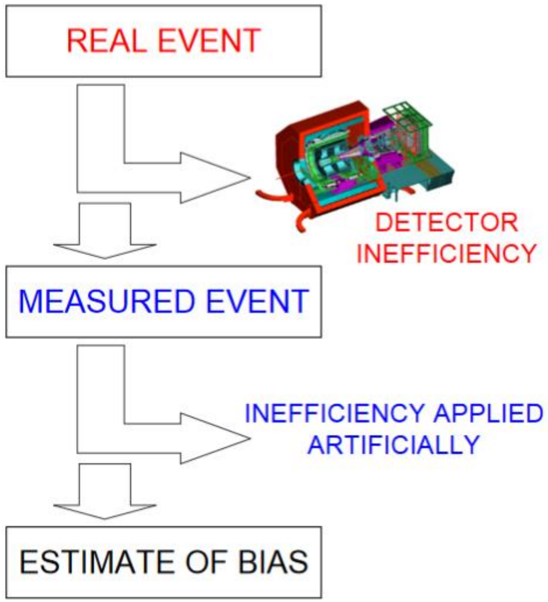
MC Truth (all primaries) → 80% → MC Truth (reco. primaries) → +2% → MC Truth (reco. primaries + secondaries) → Reco. quantities (primaries + secondaries)

only resolution

Further Corrections

- Underlying-event specific effects
  - Not reconstructed leading track, leads to re-orientation of towards, transverse, and away region
  - E.g. about 5% migration about towards → transverse
- Correction
  - Based on MC (implies MC dependence)
  - Data-driven approach
    - Apply tracking efficiency 2nd time to the leading track
    - If reconstructed, fill normally
    - If not, use sub leading track to orientate event



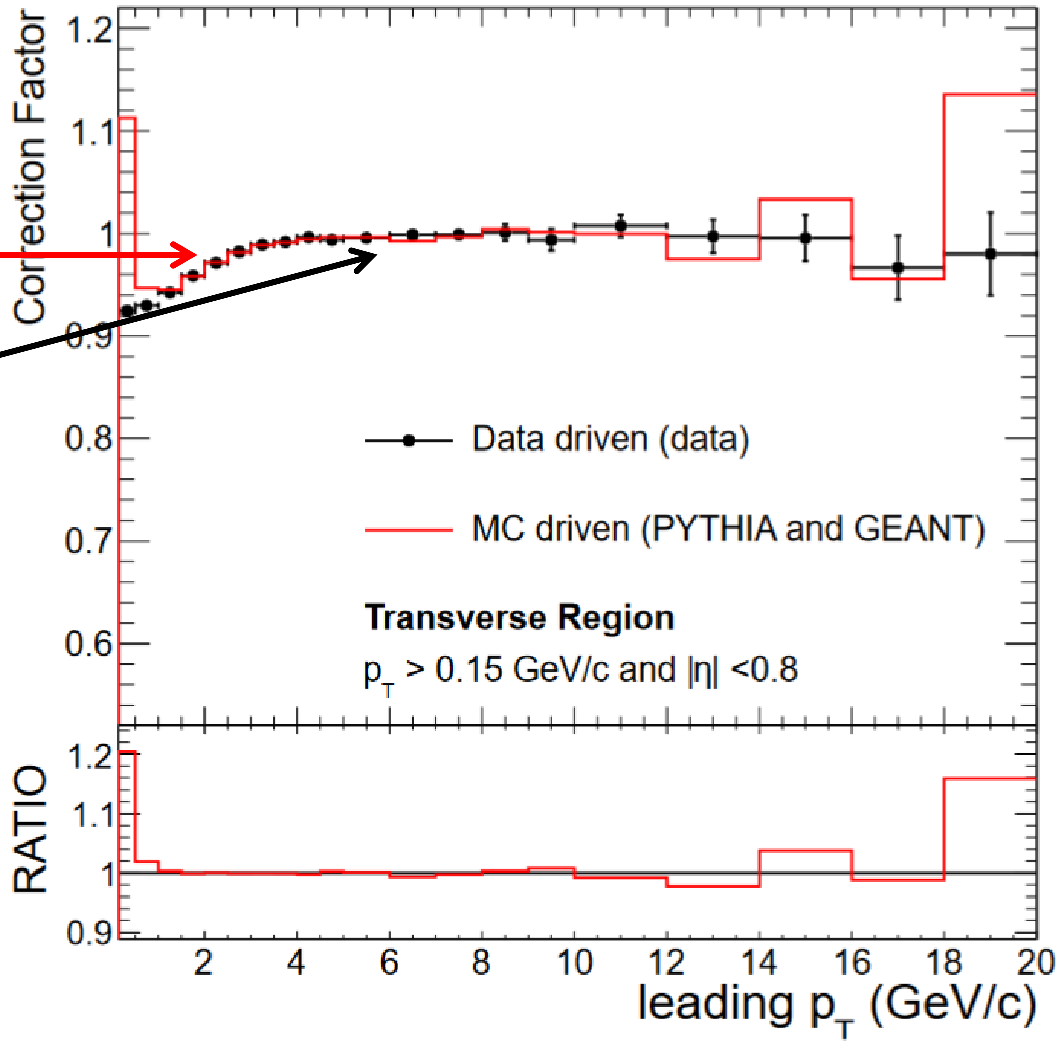


Re-orientation Correction

How to measure

MC driven

Data driven

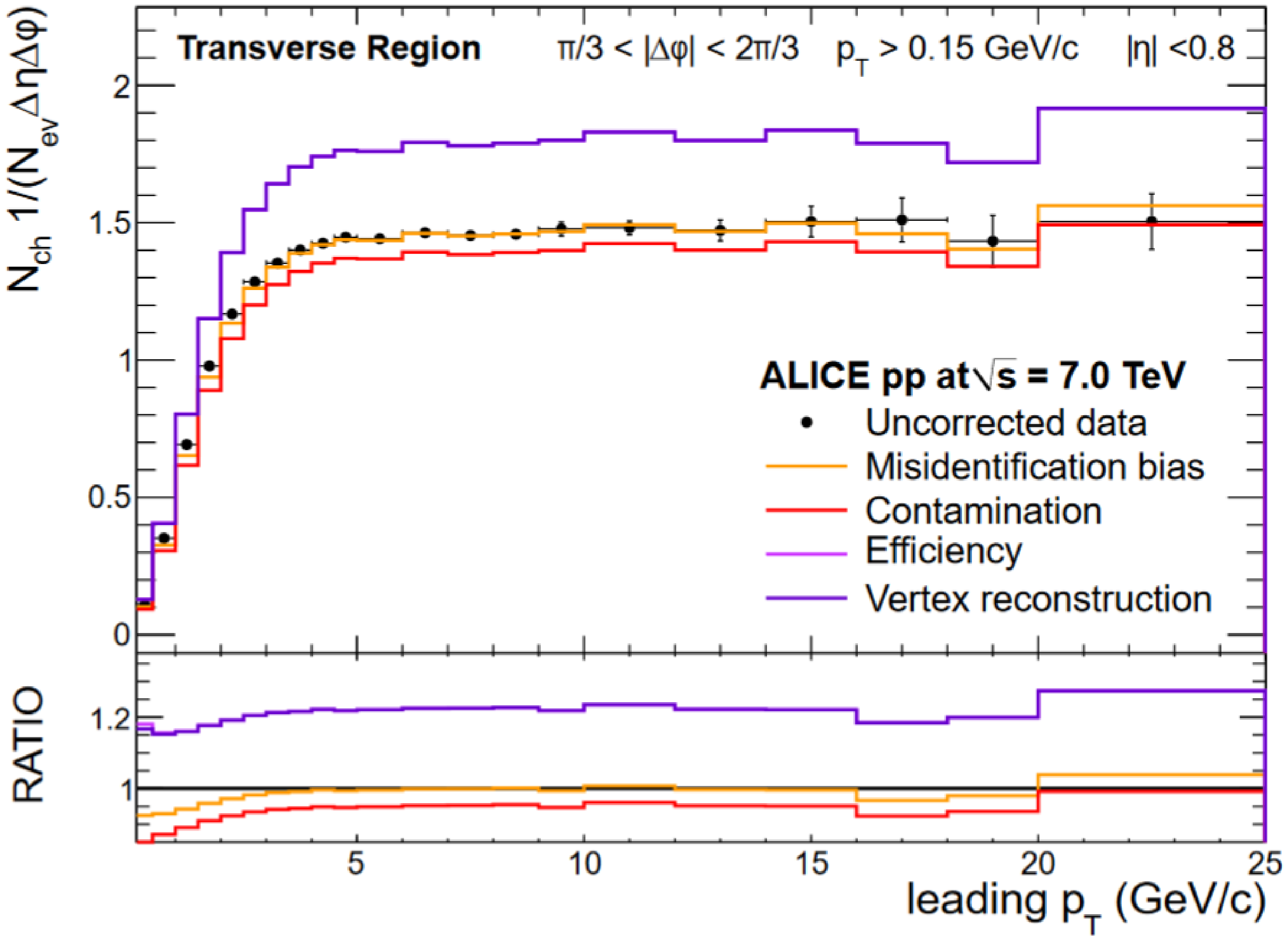


Good agreement except at low p_T (due to "event loss" when efficiency is applied 2nd time)

→ difference considered for the systematic uncertainties

Overview: Corrections on Data

How to measure



Tracking efficiency
Event re-orientation
Contamination

Tracking efficiency
Event re-orientation
Contamination

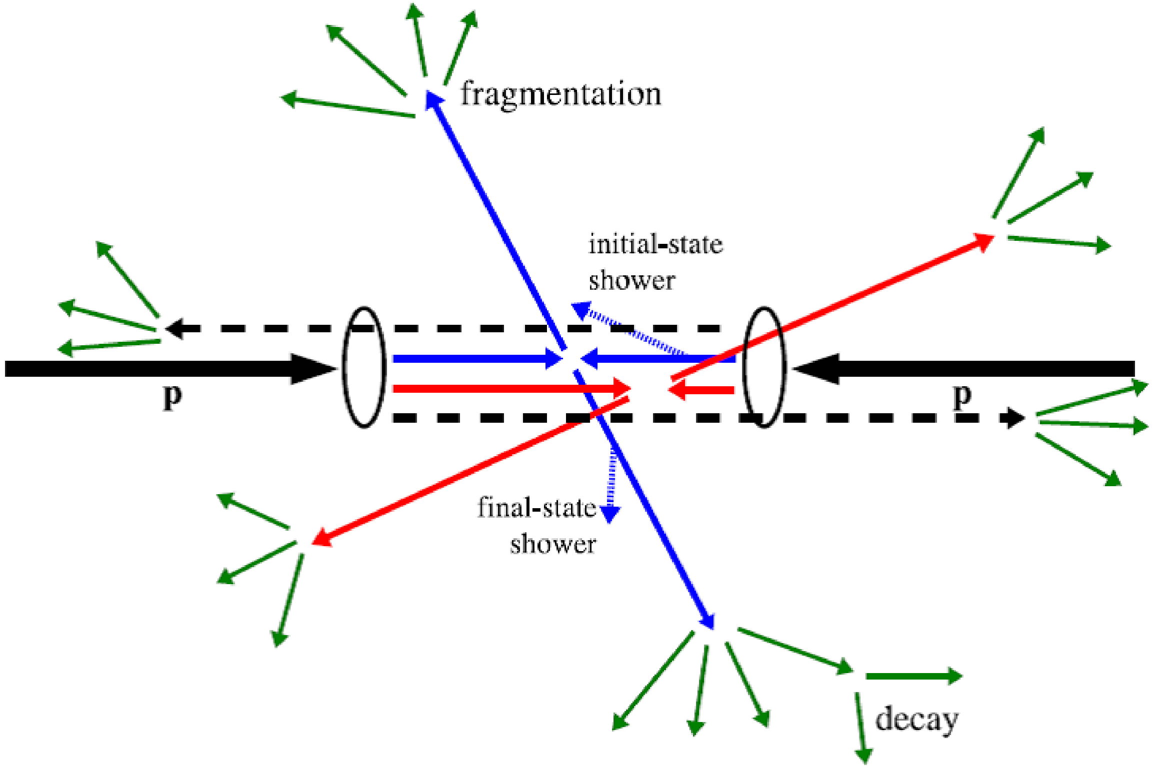
Summary
Underlying Event

- Underlying event observables characterize activity relative to the hardest scattering
- Important tool for MC tuning and modelling

- Transverse region studies activity from additional parton interactions
  – With increasing $\sqrt{s}$, underlying event grows faster than average multiplicity

Uncorrelated Seeds

Uncorrelated Seeds

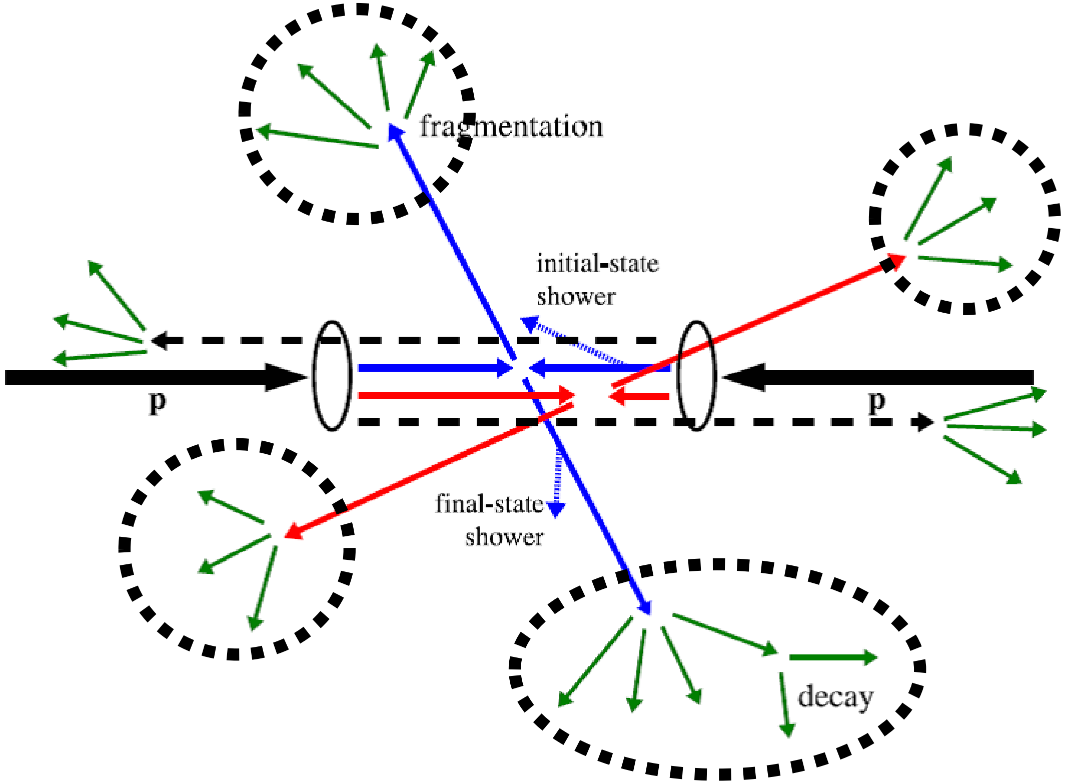


- Large range in Q^2
  - High Q^2 jets
  - Many low Q^2 processes

How to experimentally measured number of parton interactions?

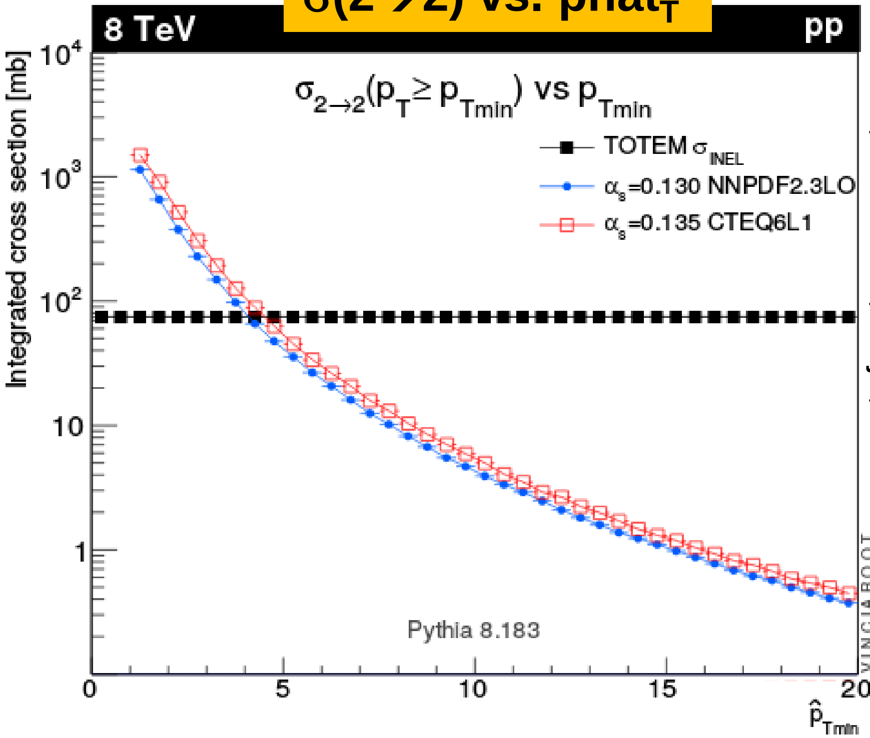
Uncorrelated Seeds

- Identify sets of particles stemming from the same parton interactions (= seed)



At high Q^2, traditional jet finding → identify each jet
At low Q^2, 1-2 particles → statistical approach

σ(2→2) vs. phat$_T$

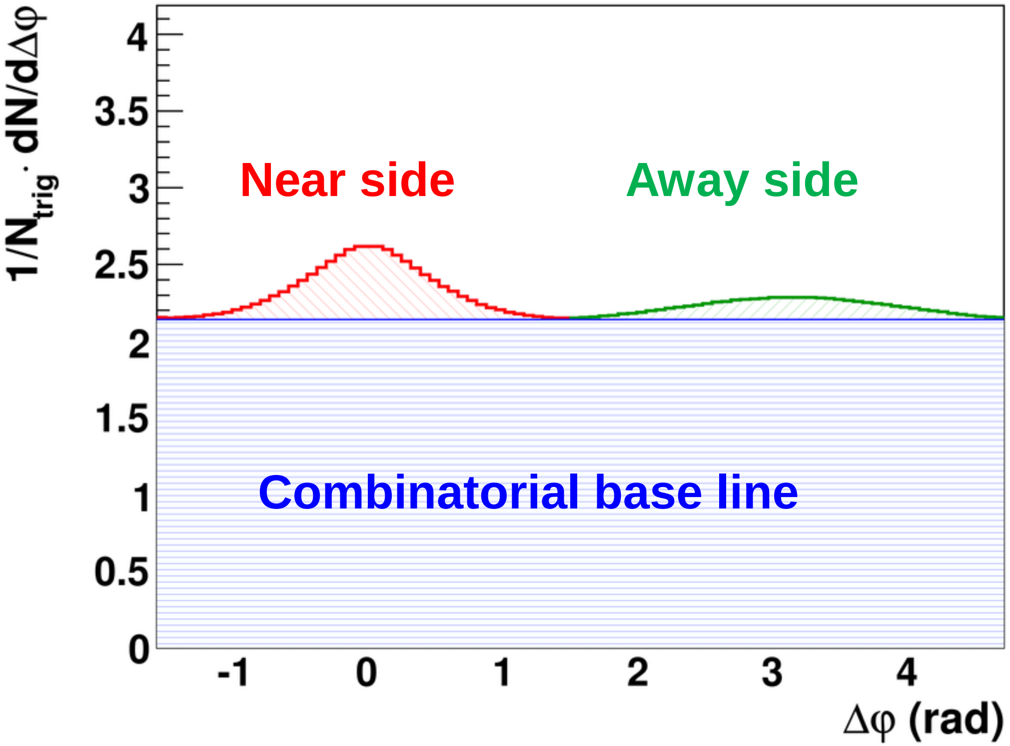


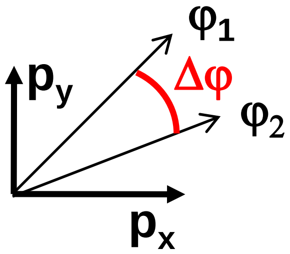
Skands, Carrazza, Rojo, arXiv:1404.5630

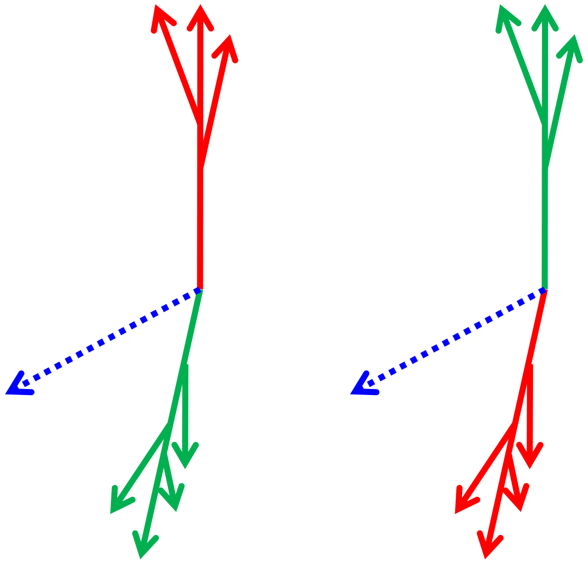
If we want to get a handle on the overall number of MPI, low Q^2 processes crucial

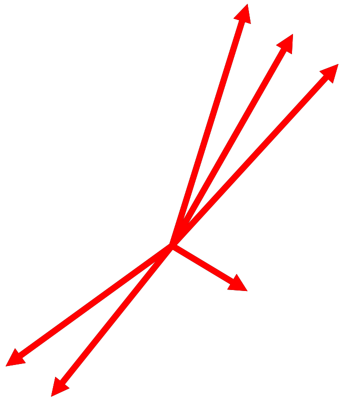
Experimental Approach

- Correlate pairs of particles
- Record azimuthal differences









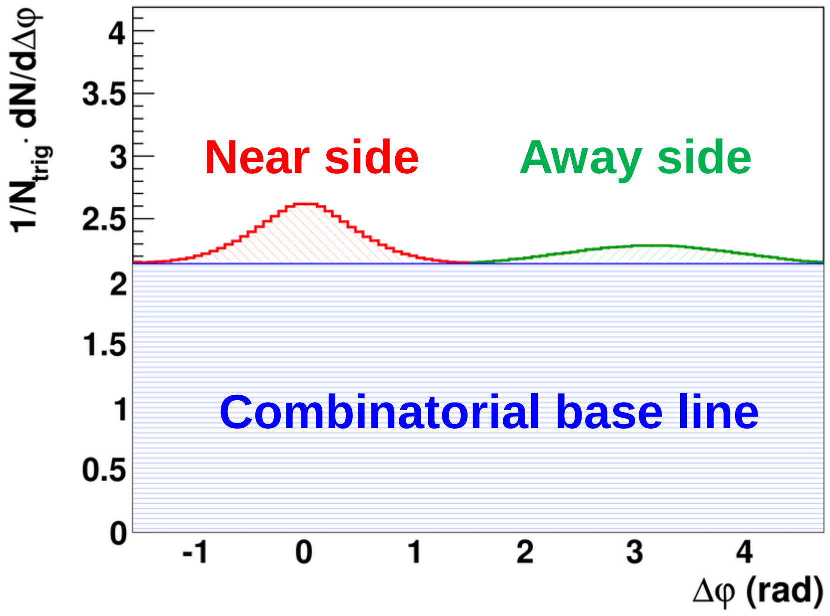
trigger particle
associated particle

$p_{T,assoc} < p_{T,trig}$

Both jet sides can contribute to the near side and away side

Pair Yield & Uncorrelated Seeds

- Pair yield $\dfrac{1}{N_{trig}} \dfrac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta}$
- Number of triggers N_{trig}
- Number of associated particles
  - on the near side
  - on the away side
- Derive uncorrelated seeds



$$\left\langle N_{uncorrelated\ seeds} \right\rangle = \frac{\left\langle N_{trig} \right\rangle}{\left\langle 1 + N_{assoc,NS} + N_{assoc,AS} \right\rangle}$$

Total number of particles

How many particles belong "together"

trigger particle

Pair Yield

- In symmetric p_T bins, with $p_{T,assoc} < p_{T,trig}$
- With n particles within a minijet, n(n-1)/2 pairs can be formed

$$\frac{\langle N_{pair} \rangle}{\langle N_{trig} \rangle} = \frac{\langle n(n-1)/2 \rangle}{\langle n \rangle} = \frac{1}{2}\left(\frac{\langle n^2 \rangle}{\langle n \rangle} - 1 \right)$$

- Depends on second moment $\langle n^2 \rangle$ of distribution P(n)
- Limit: small $\langle n \rangle$ and monotonically falling P(n)

$$\frac{1}{2}\left(\frac{\langle n^2 \rangle}{\langle n \rangle} - 1 \right) \approx \underbrace{\frac{\langle n \rangle}{1 - P(0)}}_{\text{Mean number of particles if at least one particle produced}} - 1$$

Mean number of particles if at least one particle produced → **Associated particles to a trigger**

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Pair Yield (2)

- Test $\frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right) \approx \frac{\langle n\rangle}{1-P(0)}-1$
- Geometrical row

$$P(n)=(1-q)q^n \;\rightarrow\; \frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\langle n\rangle=\frac{\langle n\rangle}{1-P(0)}$$

Exact!

- Poisson distribution

$$P(n)=\frac{\mu^n e^{-\mu}}{n!} \;\rightarrow\; \frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\frac{\mu}{2} \qquad \frac{\langle n\rangle}{1-P(0)}-1=\frac{\mu}{2}-\frac{\mu^2}{6}+\ldots$$

First order

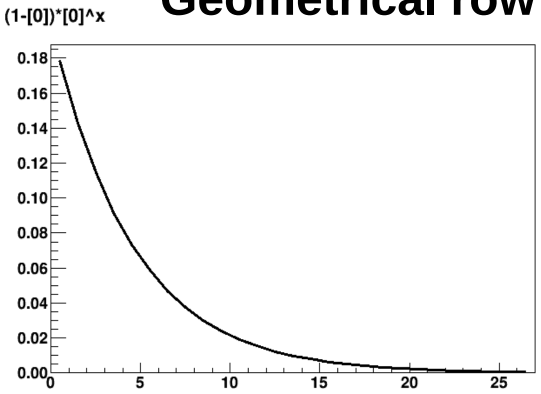
- Log series

$$P(n)=-\frac{1}{\ln(1-p)}\frac{p^n}{n}$$

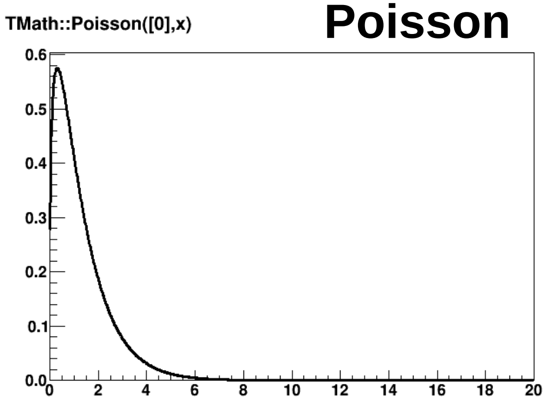
$$\rightarrow \frac{1}{2}\left(\frac{\langle n^2\rangle}{\langle n\rangle}-1\right)=\frac{p}{2(1-p)} \qquad \frac{\langle n\rangle}{1-P(0)}-1=\frac{p}{2(1-p)}+\frac{p^2}{3(1-p)}+\ldots$$

First order

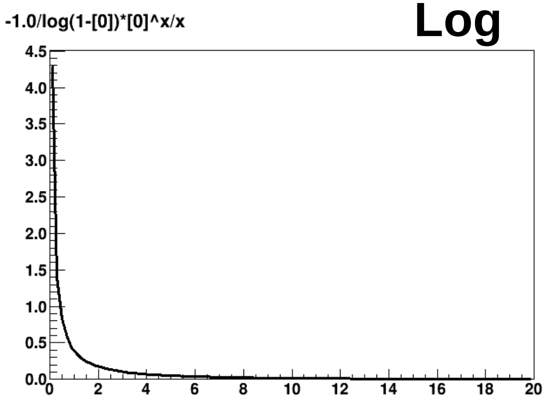
Geometrical row



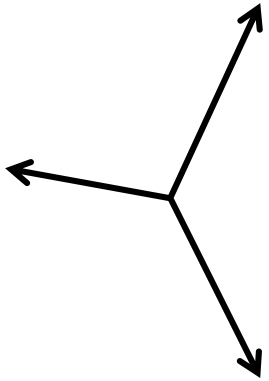
Poisson



Log



Uncorrelated Seeds: Numerical Example



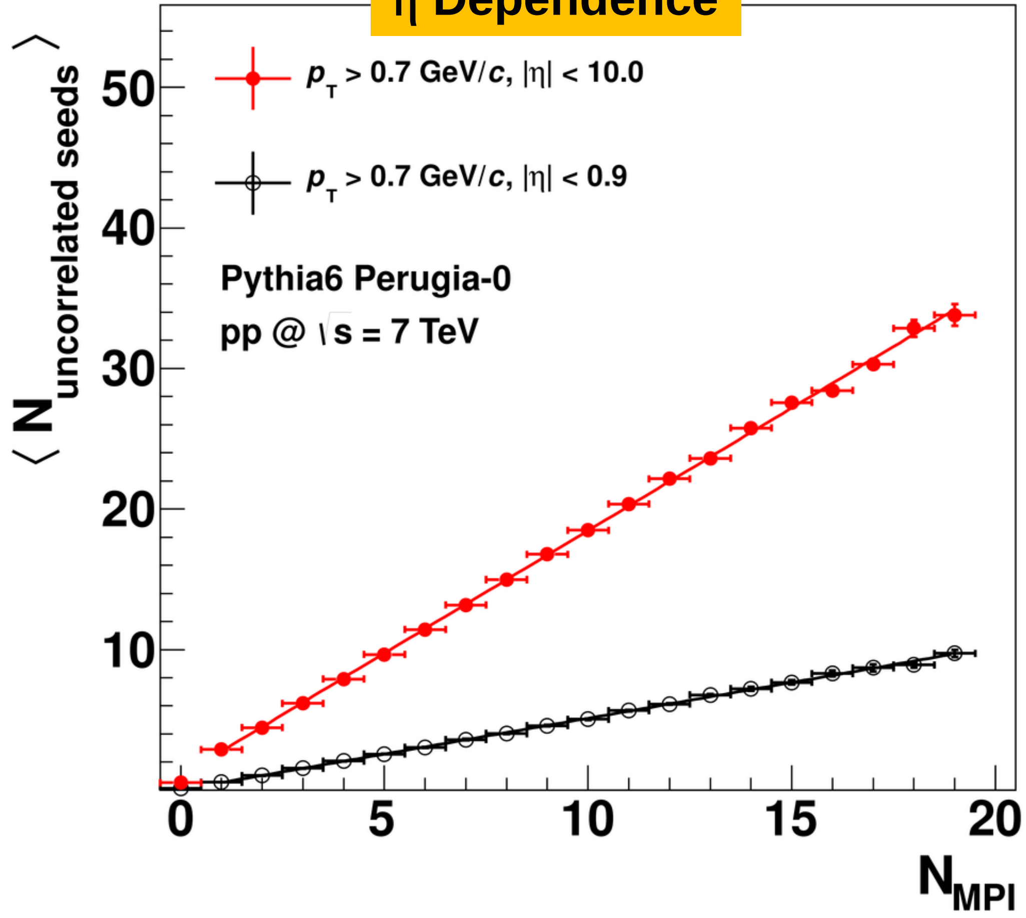
Seeds (true)	3
N_{trig}	3
N_{assoc}	0 / 3 = 0
$N_{uncorrelated\ seeds}$	3 / (1 + 0) = 3

$$\frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta} \qquad \left\langle N_{uncorrelated\ seeds} \right\rangle = \frac{\left\langle N_{trig} \right\rangle}{\left\langle 1 + N_{assoc,NS} + N_{assoc,AS} \right\rangle}$$

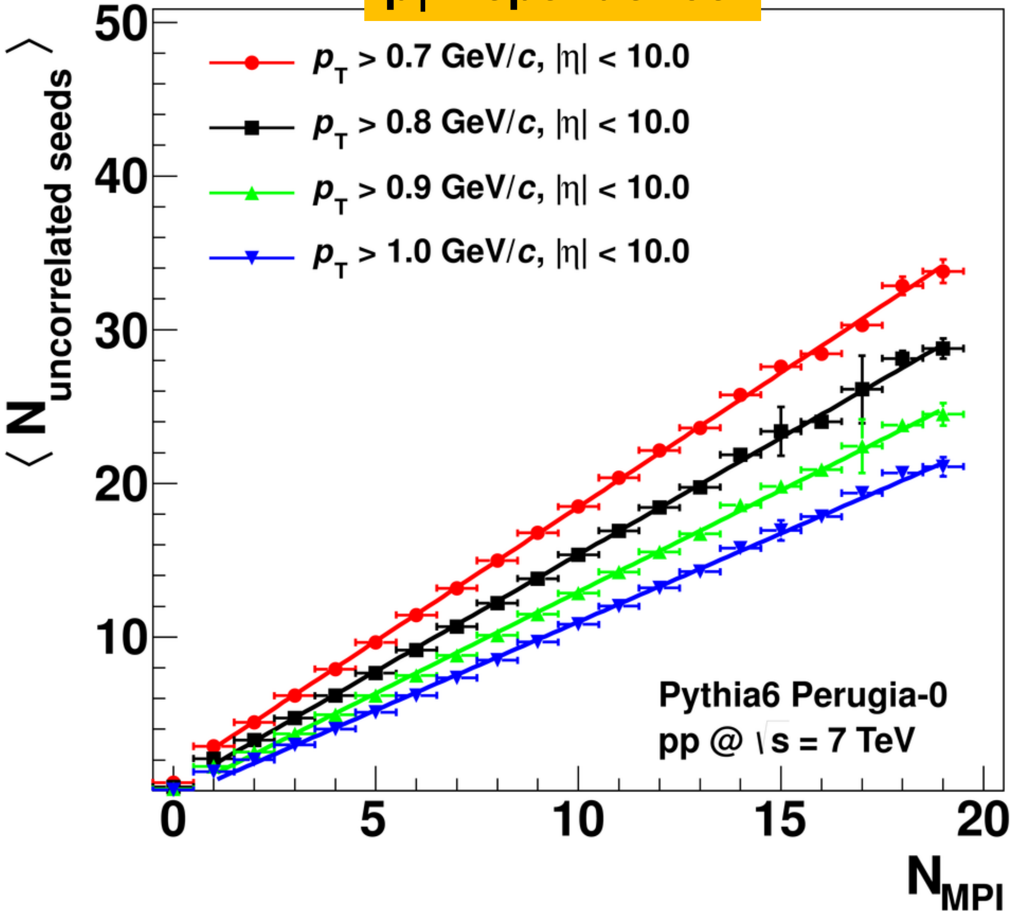
Approximation!

Relation of Uncorrelated Seeds and MPI

η Dependence



p_T Dependence



In Pythia, clear proportionality

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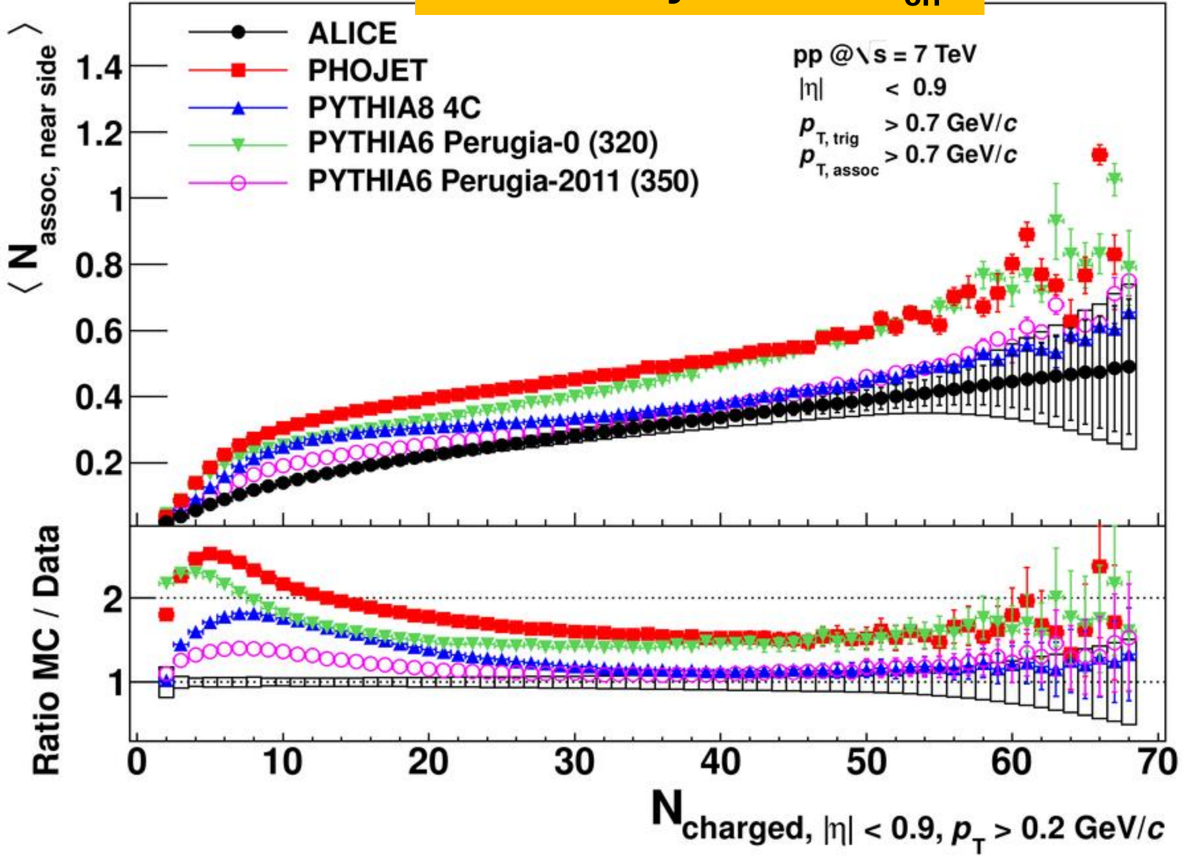
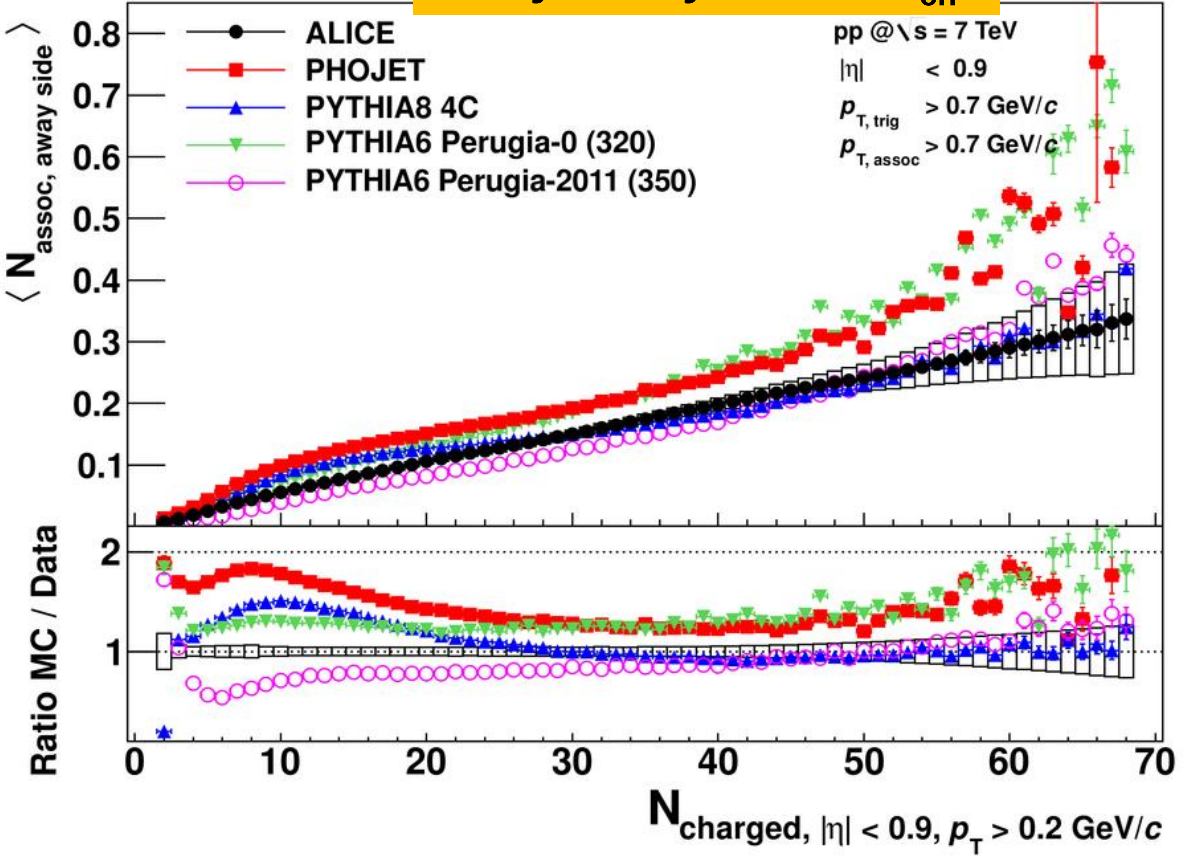
Results: Pair Yields

Near-side yield vs. N_{ch}



Away-side yield vs. N_{ch}



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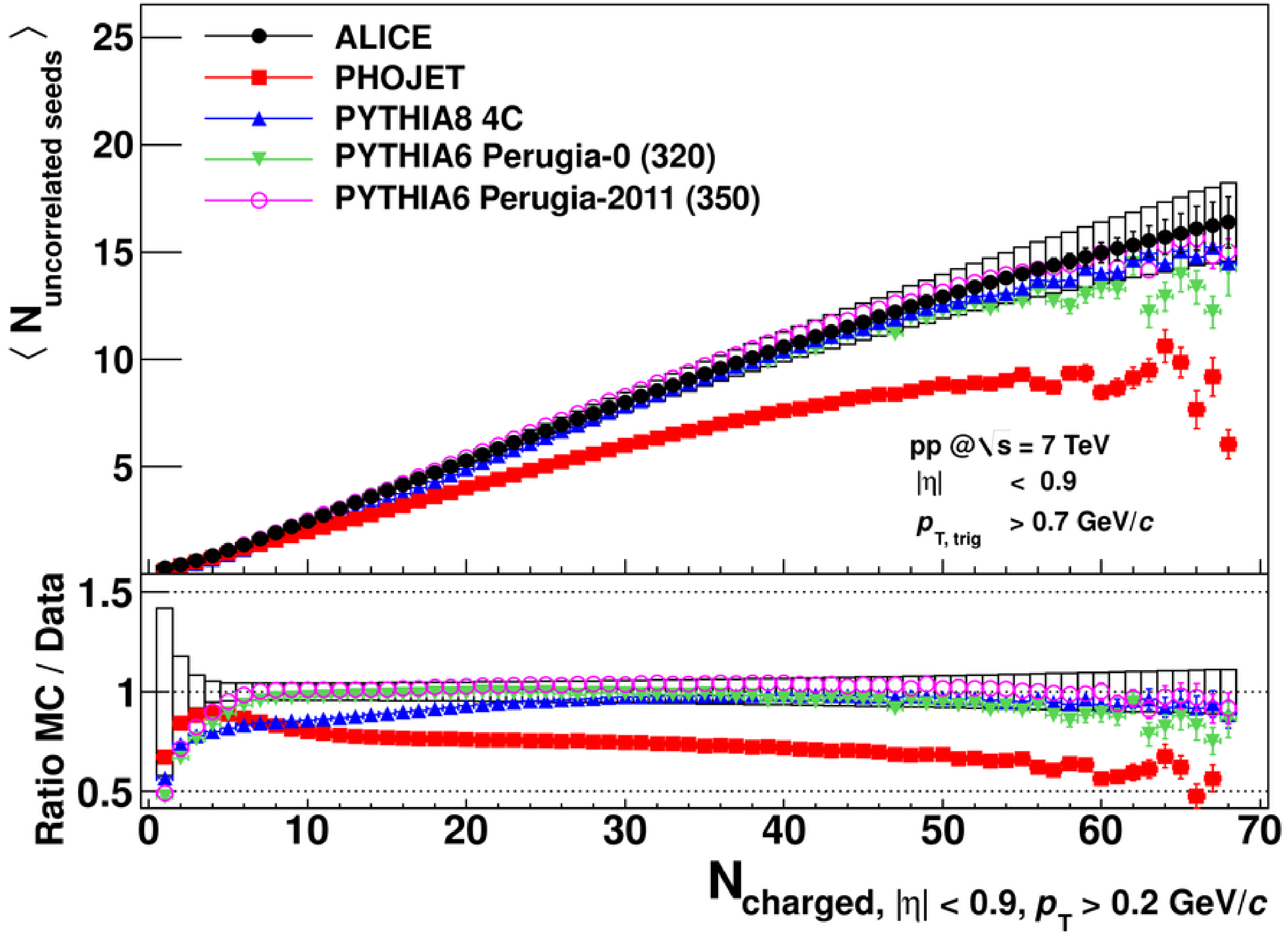
Results: Uncorrelated Seeds



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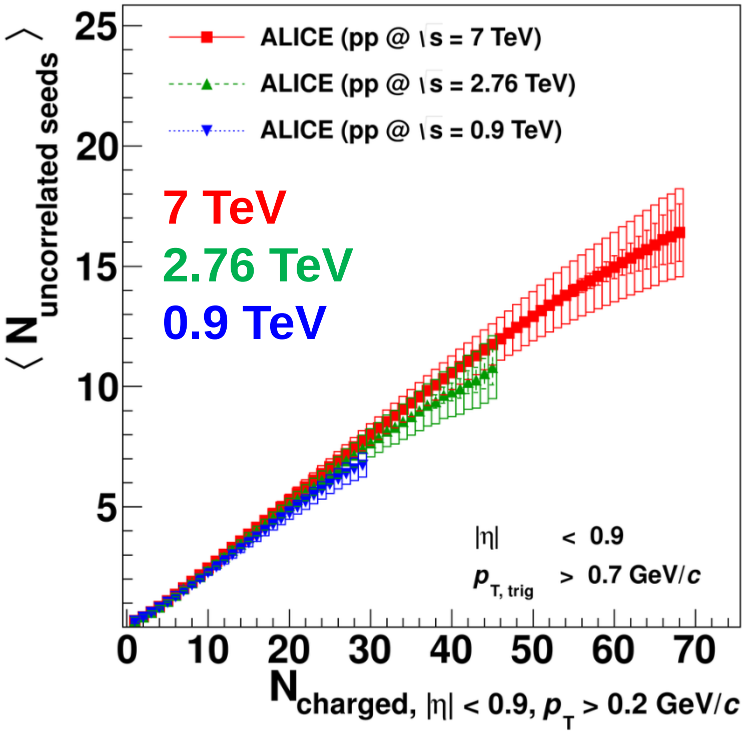
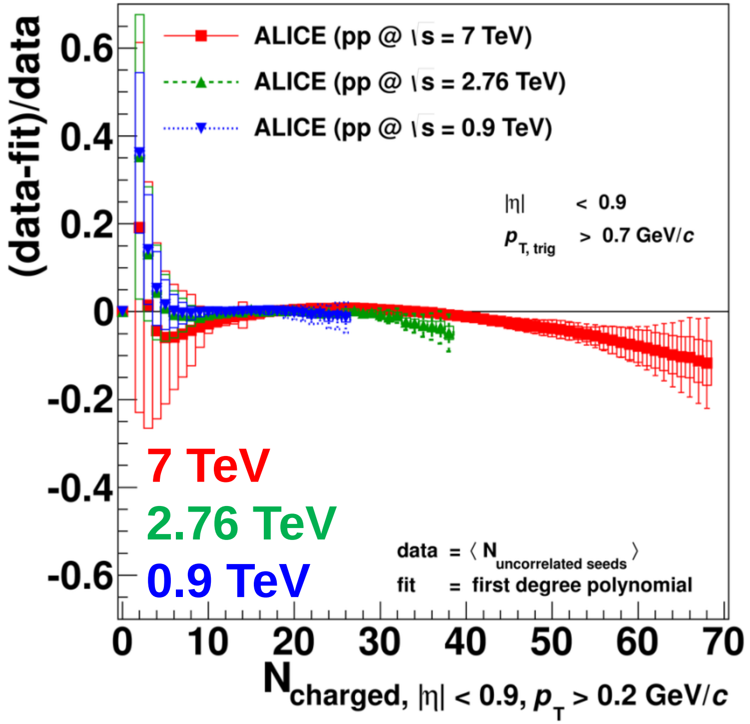
Uncorrelated Seeds

- Uncorrelated seeds (~ MPI) increase linearly with N_{ch}
- At large N_{ch}, limit of MPI?
  (i.e., larger multiplicity by fluctuation, not by additional MPI)





New data will tell…

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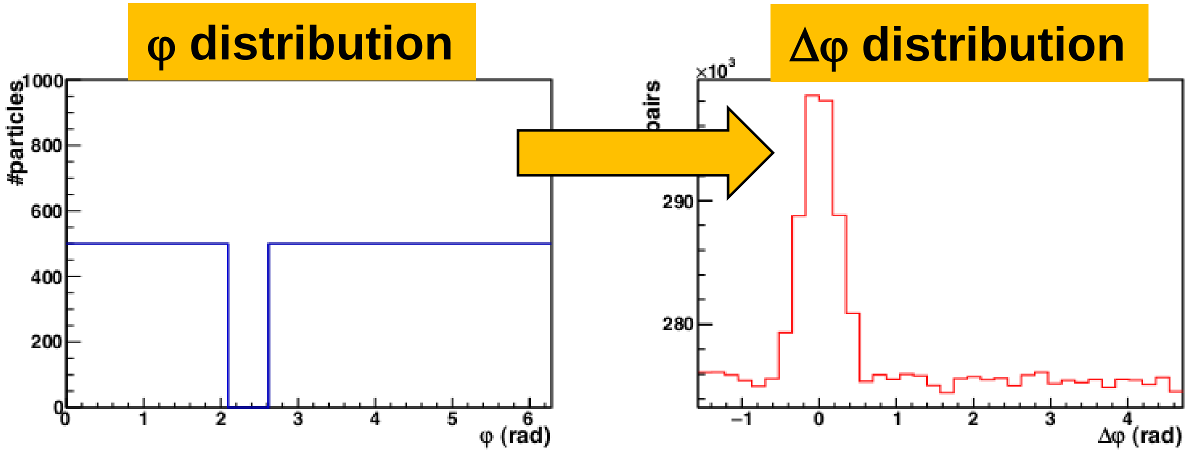
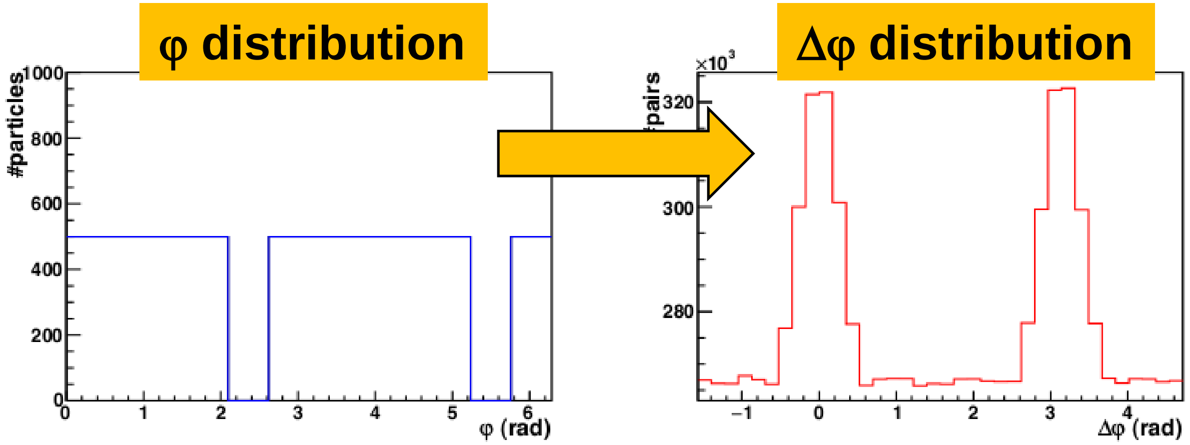
Event Mixing

How to measure

- Correlation measurements sensitive to detector acceptance
  - “Background” from non-uniform detector acceptance easily larger than signal
- Drawing particles from uniform distribution with
  - One gap → peak structure in two-particle $\Delta\varphi$ distribution
  - Two gaps → back-to-back structure in two-particle $\Delta\varphi$ distribution



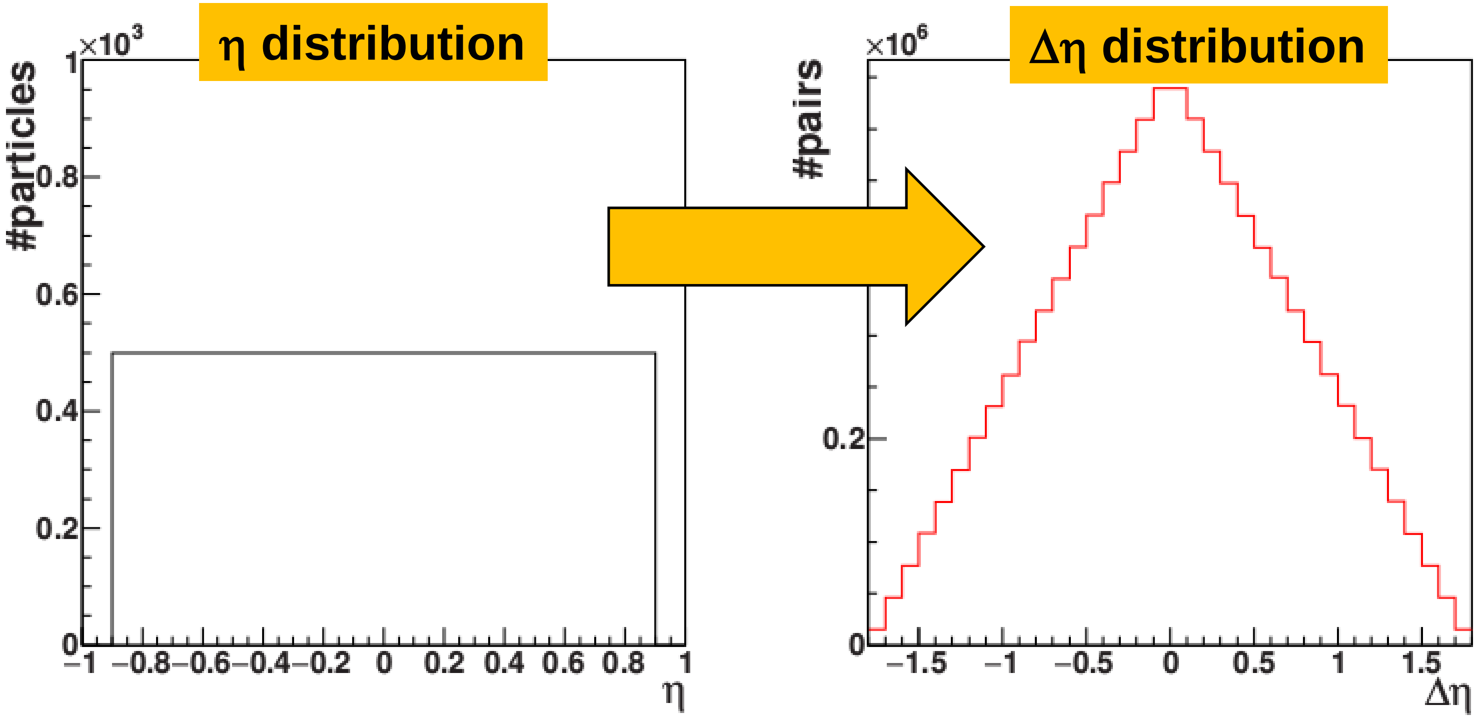


Figures: Emilia Leogrande

Limited η Acceptance

How to measure

- Detector limit in pseudorapidity
- Leads to tent in two-particle Δη distribution



Figures: Emilia Leogrande

Event Mixing

Not any two events can be mixed! Similar multiplicity and detector acceptance (z vertex) needed.

- These effects can be estimated and corrected data-driven
- Signal S contains correlation within an event

$$S(\Delta\varphi,\Delta\eta) = \frac{1}{N_{trig}} \frac{d^2 N_{pairs,same}}{d\Delta\varphi d\Delta\eta}$$

- Background B contains "correlation" between different events

$$B(\Delta\varphi,\Delta\eta) = \alpha \frac{1}{N_{trig}} \frac{d^2 N_{pairs,mixed}}{d\Delta\varphi d\Delta\eta}$$

  - Estimates pair efficiency and acceptance
  - Normalized such that B(0,0) = 1
    - Two particles going in the same direction, see the same acceptance

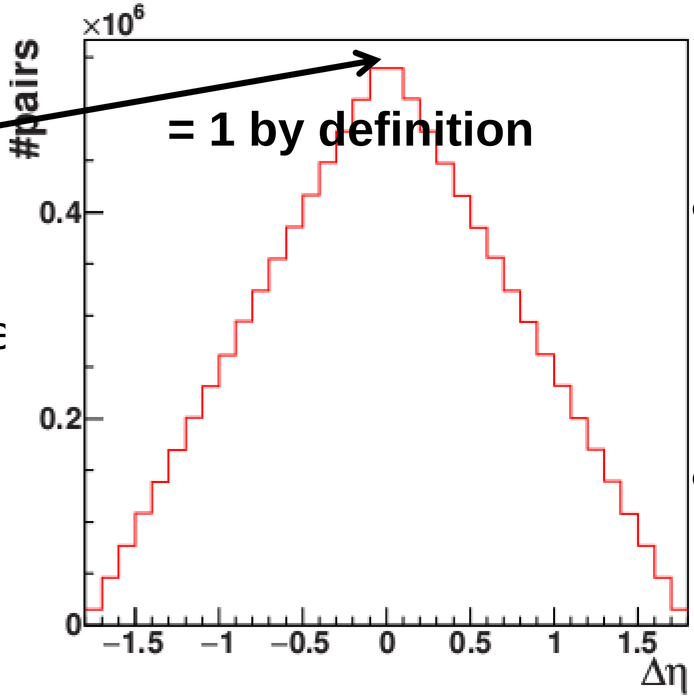


Figure: Emilia Leogrande

- Associated yield per trigger particle

$$\frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta} = \frac{S(\Delta\varphi,\Delta\eta)}{B(\Delta\varphi,\Delta\eta)}$$

Summary
Uncorrelated Seeds

- Two-particle correlations measure associated particle yields
- Allows to calculate uncorrelated seeds

- These are proportional in Pythia to the number of MPI
- Direct access to number of low Q^2 scatterings

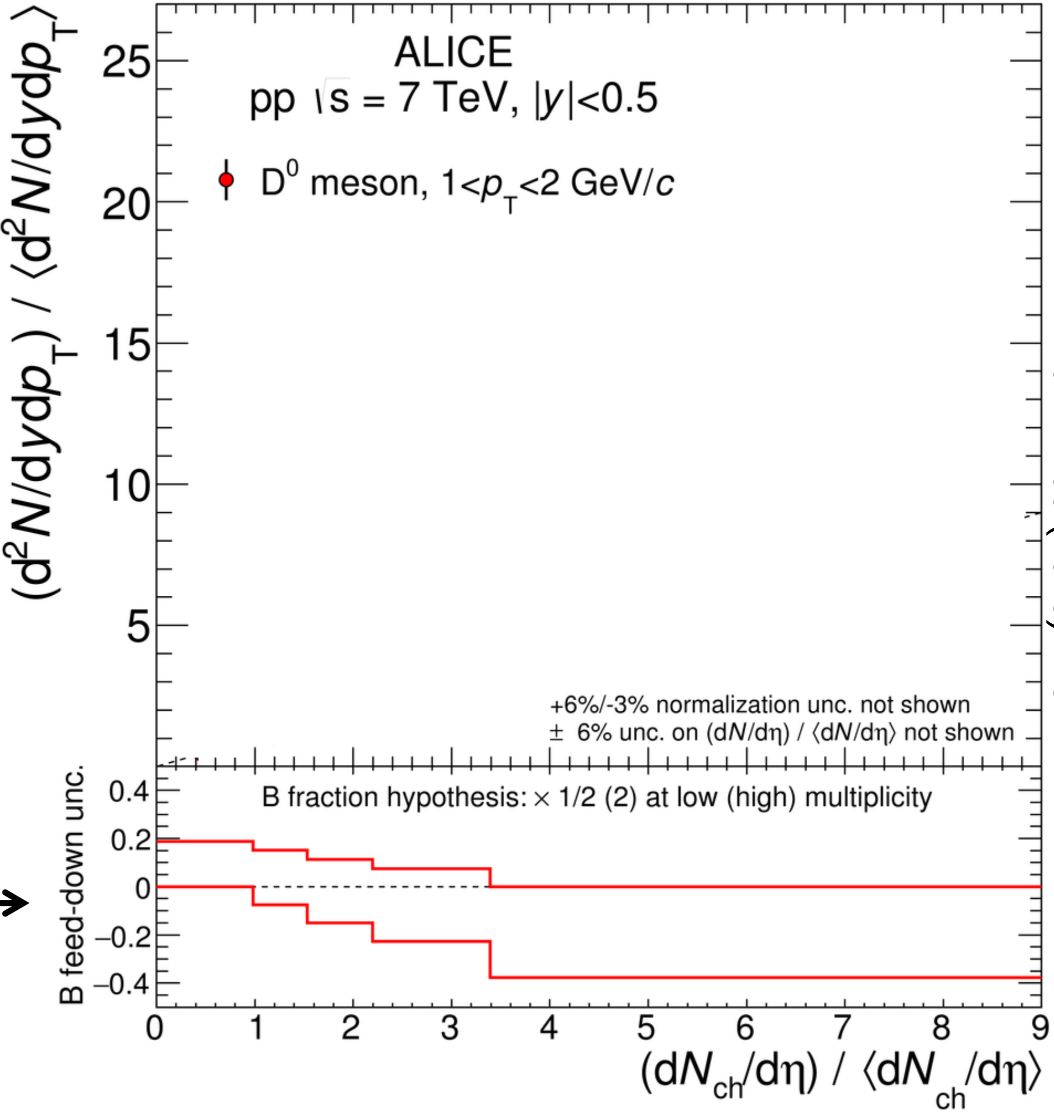
- At high multiplicity, hint of limit in the number of MPI

Hard Probes vs. Multiplicity

Hard Probes

- Multiplicity, underlying event activity and uncorrelated seeds probe soft part of MPI
- How does hard MPI production behave?
- How are the soft and hard related?
- Measurement of D and J/ψ
  - c produced in hard scattering (m_c = 1.28 GeV/c)

- Experimentally expressed as D/<D> vs. N_{ch}/<N_{ch}>
- For D: B feeddown fraction relevant (B → D + X)



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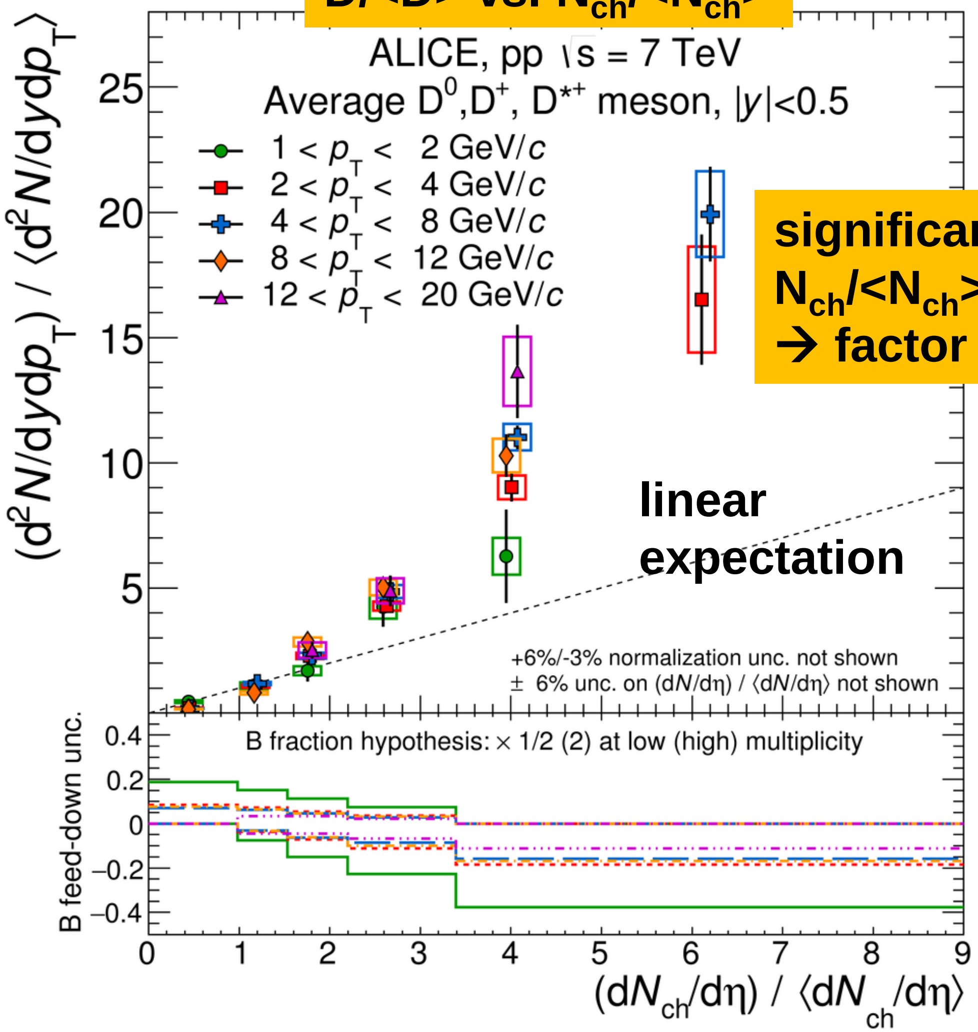
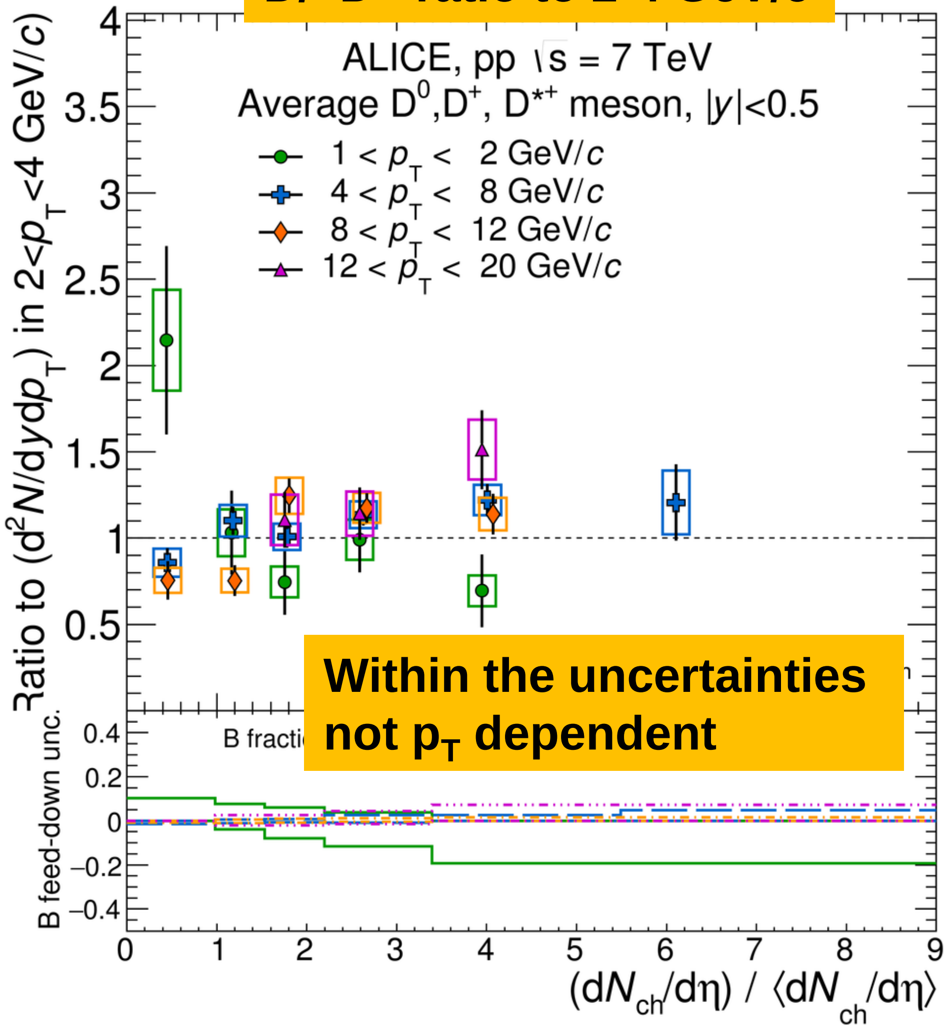
D Production vs. Multiplicity



D/<D> vs. N_{ch}/<N_{ch}>

linear expectation

significant growth above linear
N_{ch}/<N_{ch}> = 6
→ factor 15 enhancement



D/<D> ratio to 2-4 GeV/c

Within the uncertainties not p_T dependent

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Multiplicity Estimator

- D and N_{ch} measured in same rapidity
  - Autocorrelation bias?
  - Associated soft particle production with D?
- Measure D/<D> vs. forward multiplicity
  - "V0" ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$)
- Similar increase observed
  - Factor 5 at $N_{ch}/\langle N_{ch}\rangle = 3.5$
  - Multiplicity reach is smaller forward than at mid-rapidity

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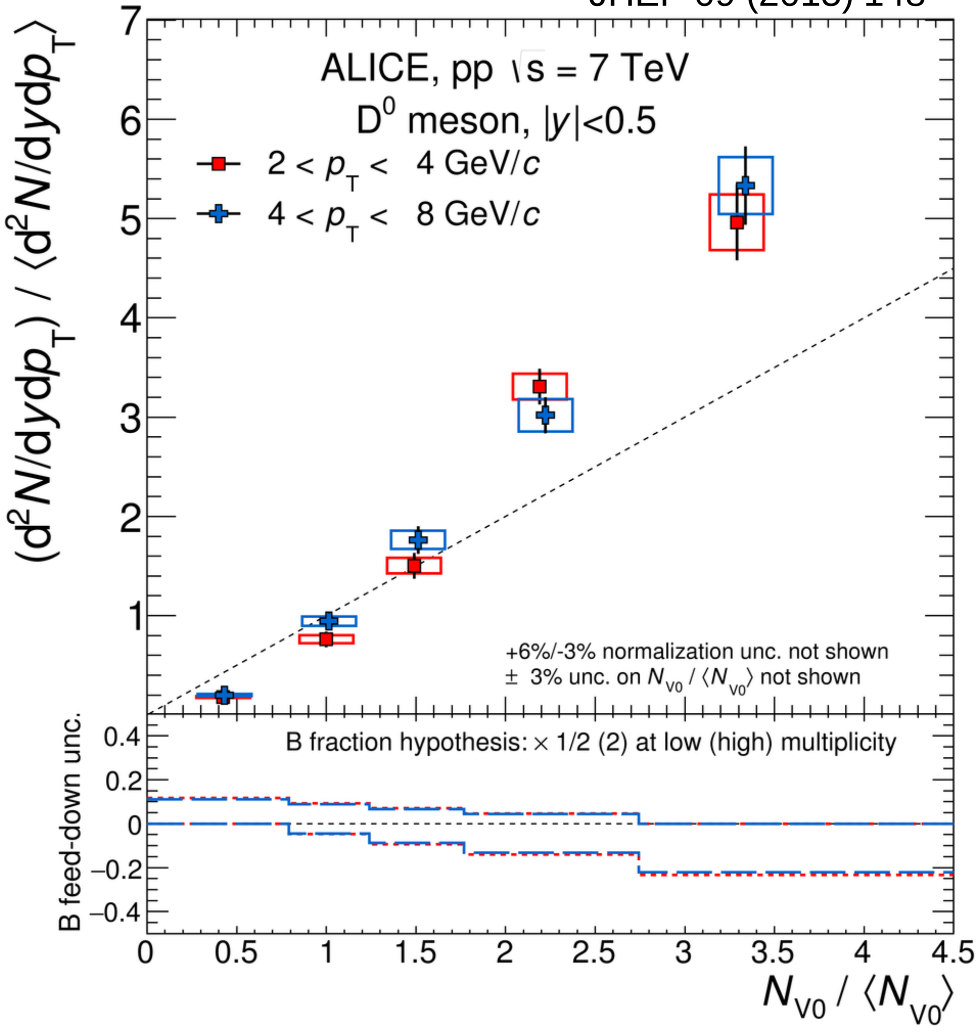
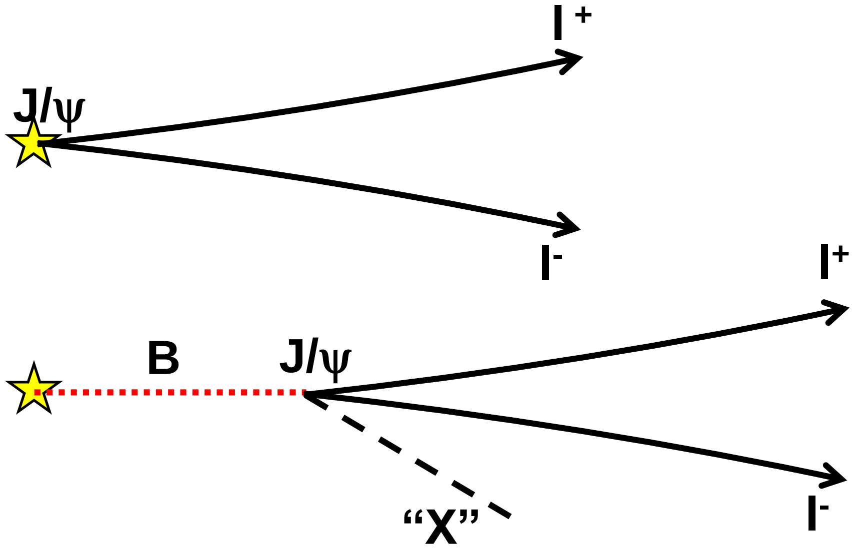


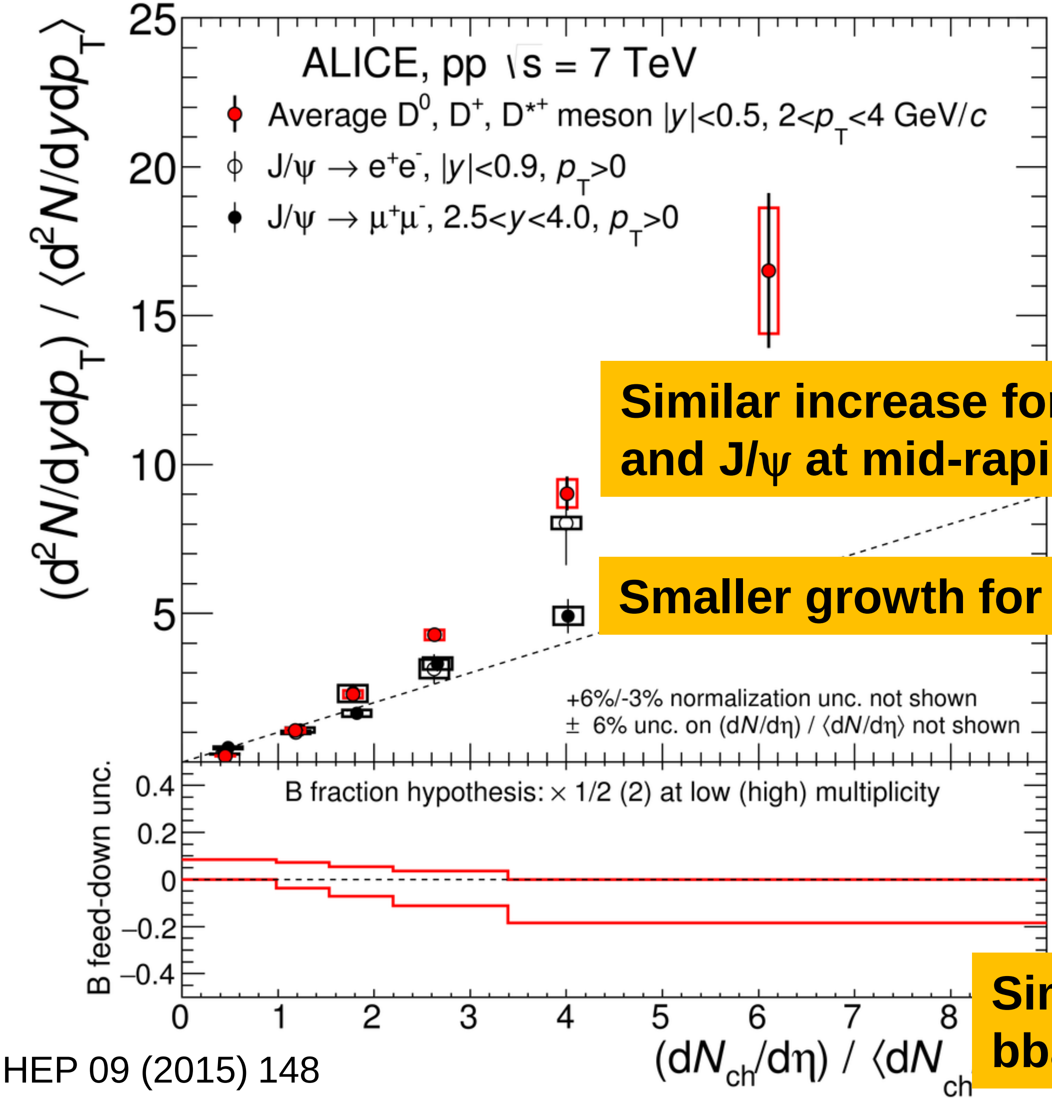
J/ψ Production

- J/ψ are produced
  - in the collision "prompt"
    [direct from process producing ccbar]
  - from the decay of a B quark "non-prompt"
    [process has produced b quark]



- Different physics
- Can be experimentally distinguished by J/ψ impact parameter

J/ψ vs. Multiplicity



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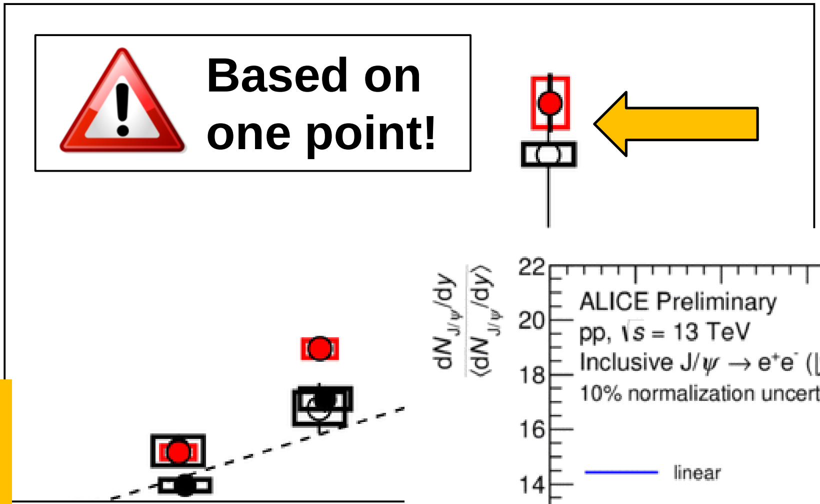
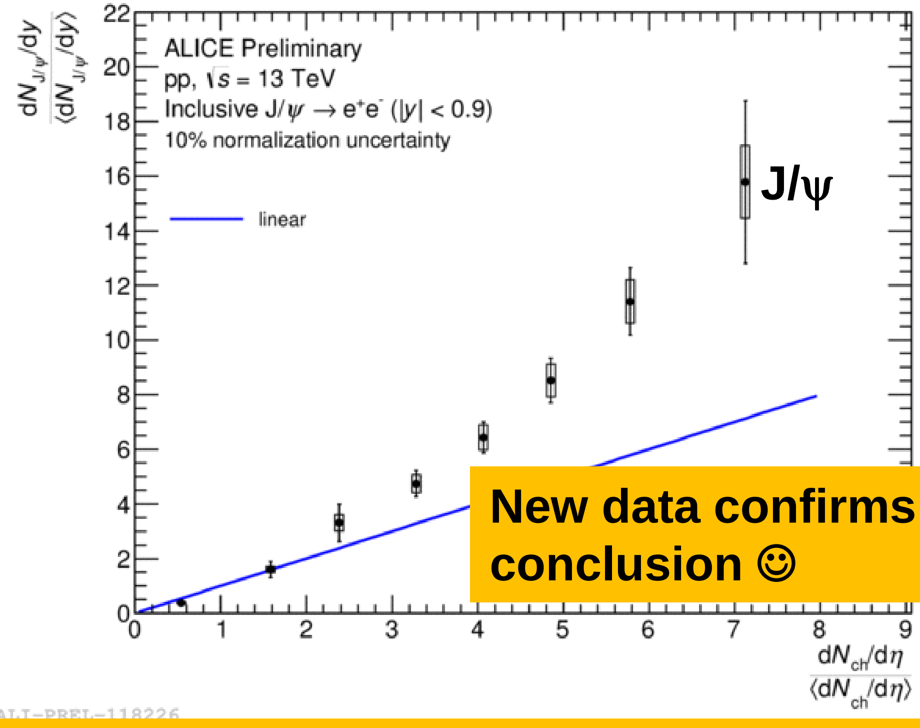


Based on one point!



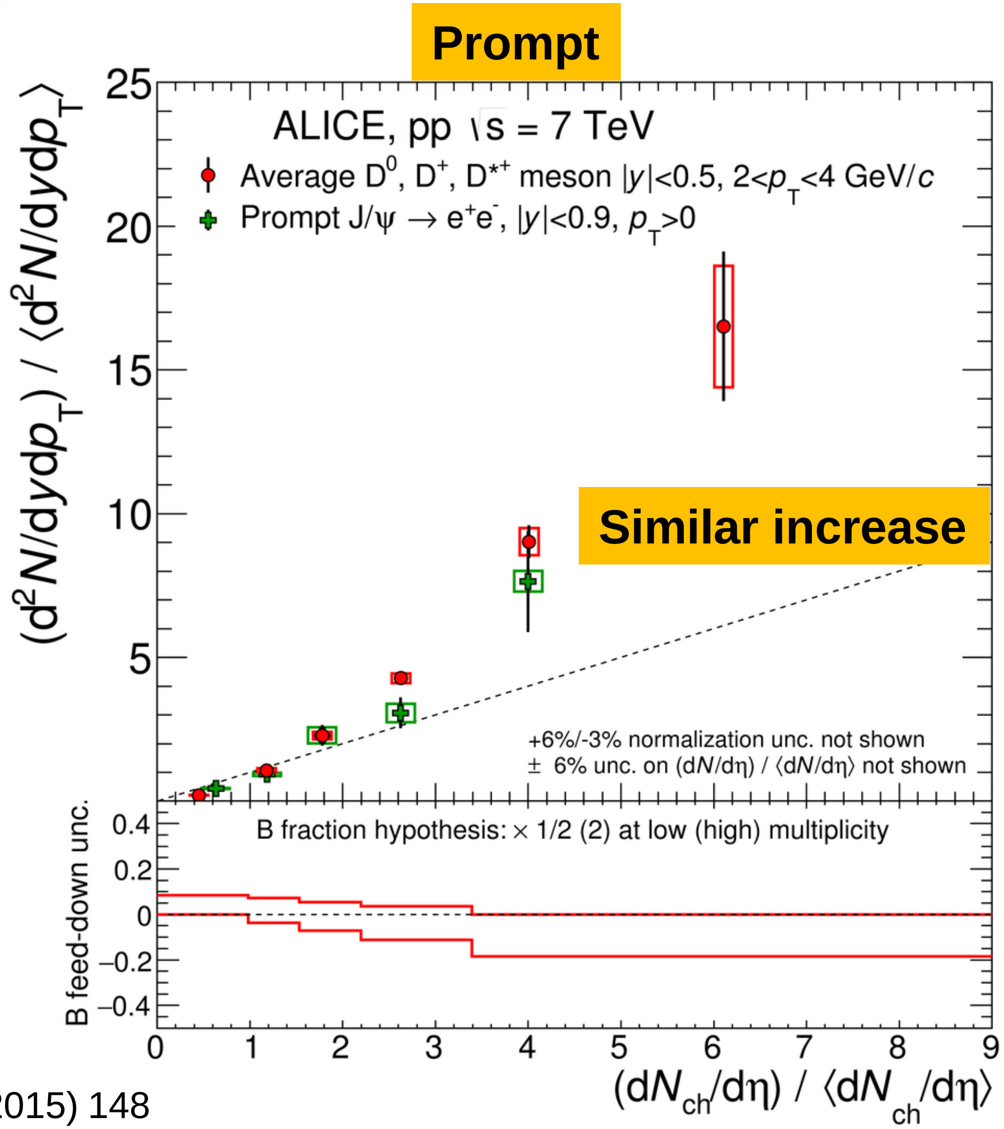
Similar increase for D and J/ψ at mid-rapidity

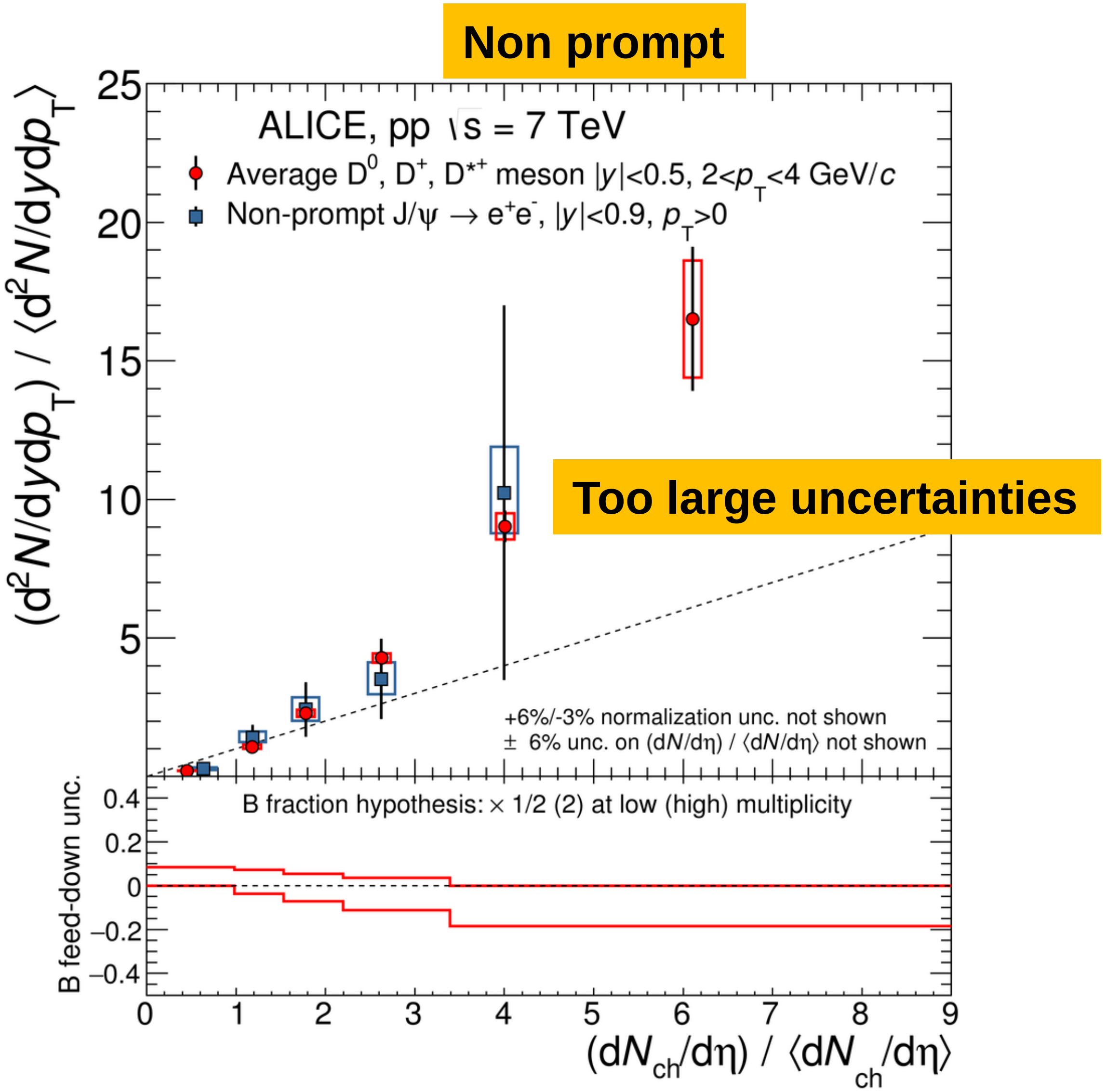
Smaller growth for forward J/ψ

New data confirms conclusion ☺

Similar increase for D and J/ψ → increase related to ccbar and bbar production process (only minor influence of hadronisation)

Prompt and Non-prompt





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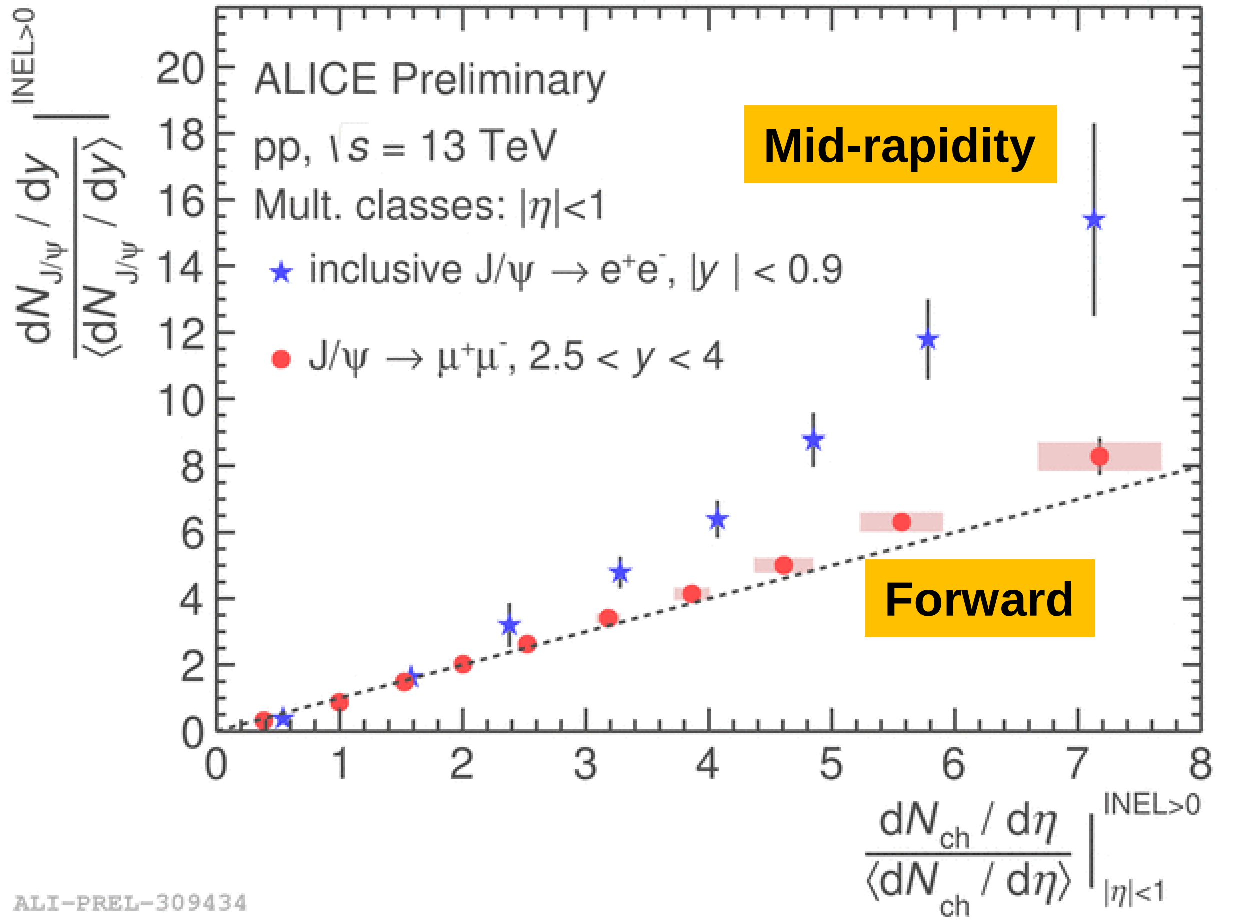
Rapidity Dependence

- Growth significantly larger at mid-rapidity than at forward rapidity
- Autocorrelation bias
  - Multiplicity measured in same phase space as hard probe
  - Discussed later

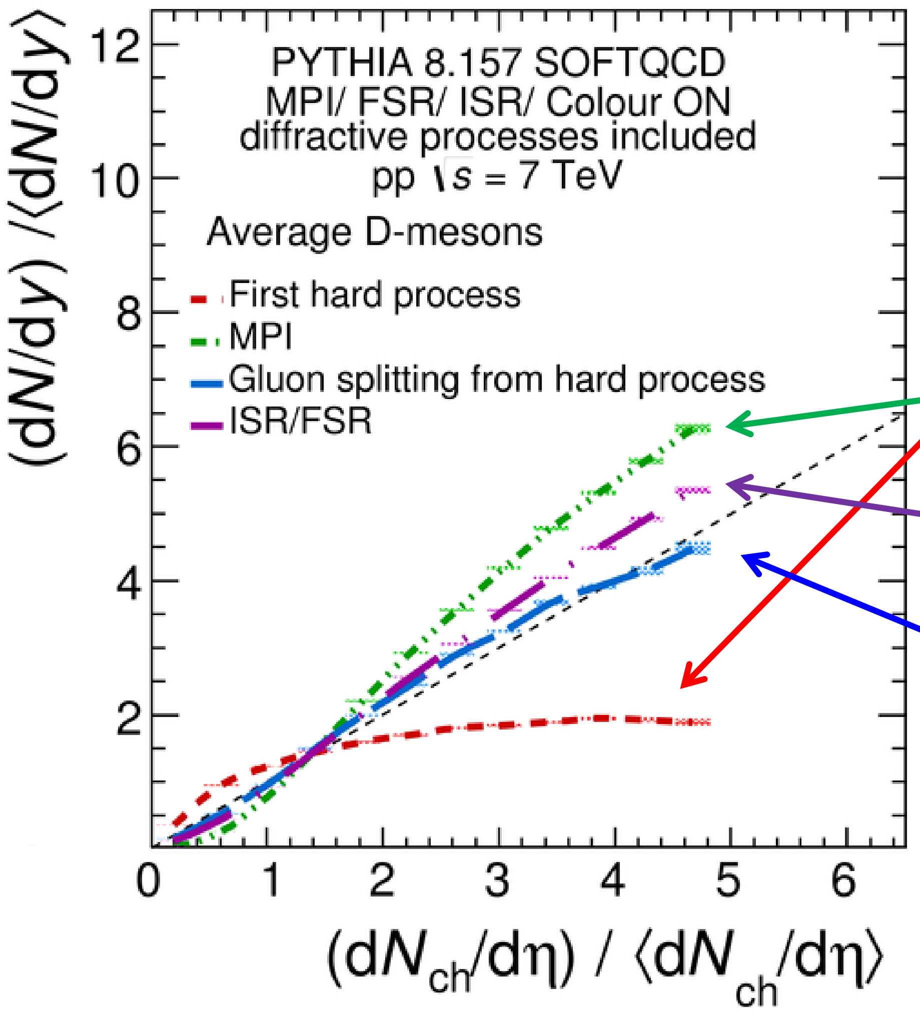


Recap

- D and J/ψ at mid rapidity grow faster than the average multiplicity
  - Within current precision: p_T independent
- Smaller growth for forward rapidity
  - At least partly an auto-correlation effect
- Within current precision, no conclusion for non-prompt component

- How to interpret this growth within a MC?

D Production in Pythia 8



First 2 → 2 scattering
- **Gluon fusion (gg → ccbar)**
- **See quark (cu → cu)**

11%

Subsequent 2 → 2 scattering (MPI)
- **Gluon fusion (gg → ccbar)**
- **See quark (cu → cu)**

21%

Gluon from Initial or final state radiation splits into c quark

62%

2 → 2 scattering produces high virtuality gluon which splits into c quark

6%

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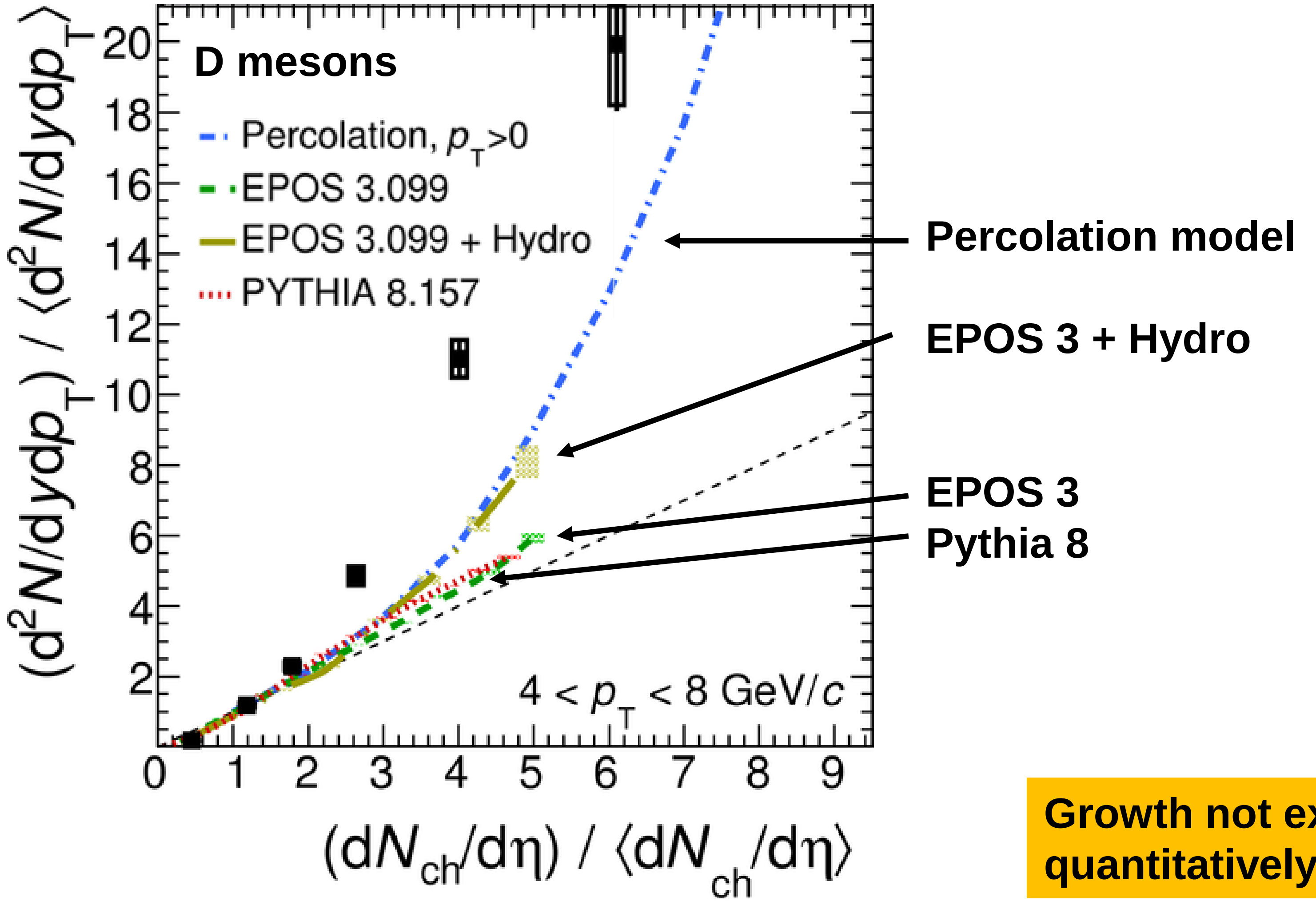
Further Model Comparisons



Growth not explained quantitatively up to now

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Summary

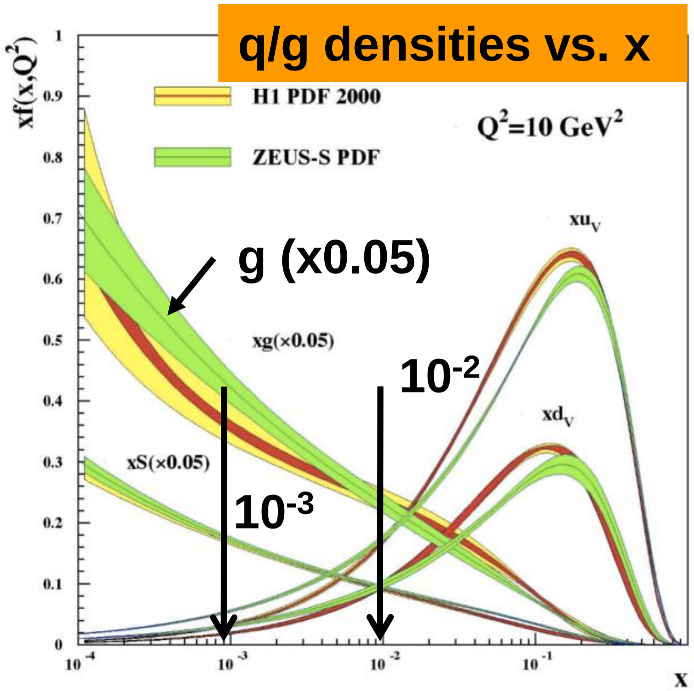
Hard Probes vs. Multiplicity

- D and J/ψ measured as a function of multiplicity
  - Proxy of the correlation of the production of hard and soft probes
- Rapidity dependence reveals auto-correlation bias

- D and J/ψ yields grow faster than multiplicity
- Quantitatively not explained by current models

Hard Double Parton Scattering

Effective Cross-Section



- Ample evidence for MPI at soft scales (Q^2 ~ few GeV^2)
- Semi-hard production also involved in MPI (D, J/ψ)
- What about higher Q^2?
  - 2 → 2 scattering probes higher x partons
    → densities are lower at larger x ($x \sim 2\, p_T / \sqrt{s}$)
- Quantified by effective cross-section σ_{eff}

$$\sigma_{eff} = \frac{\sigma_i \sigma_j}{\sigma_{ij}} \qquad \sigma_{eff} = \frac{\sigma_i^2}{2\sigma_{ii}}$$

prefactor for identical processes

  - Process independent!
  - “Encodes” PDF
  - In Eikonal picture

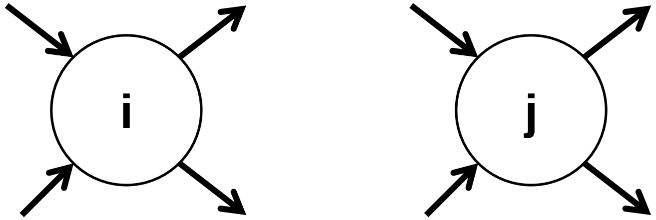
$$\sigma_{eff} = \frac{1}{\int d^2b A(b)^2} \qquad \int d^2b A(b) = 1$$

A(b) = “overlap distribution”

σ_i inclusive → if occurs twice in the same event, i needs to be counted twice

σ_{ij} only in double parton scattering (not in two separate parton scatterings)

What is σ_{eff}?



- Process i with σ_i
- Process j with σ_j
- Probability σ_{ij} to have i and j at the same time?
  - As independent processes

$$\sigma_{eff} = \frac{\sigma_i^2}{2\sigma_{ii}} \quad \sigma_{eff} = \frac{\sigma_i \sigma_j}{\sigma_{ij}}$$

Multiplying probabilities is very typical. Imagine 2 dice with 6 sides each.
What is the probability to role two times 1?
→ 1/6 * 1/6 = 1/36
However, here we look for the probability that processes occur alone or together.

- For Poisson distribution and identical processes

  $P(1) = e^{-1} \lambda$ $P(2) = e^{-2} \lambda^2/2$

  → $\sigma_{eff} = 1$
- For pp collisions at LHC, σ_{eff} ~ 20 mb
  - Prefactor encoding circumstances in which processes occur

$$\sigma_{ij} = \frac{1}{\underbrace{\sigma_{eff}}_{\text{“suppression factor”}}} \sigma_i \sigma_j$$

How to measure σ_{eff}?

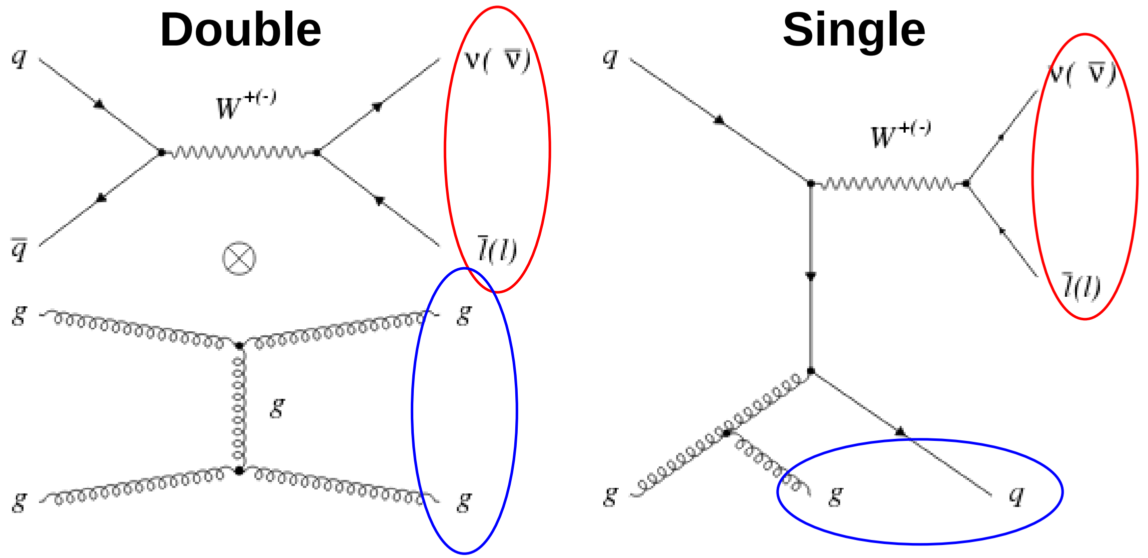
Measure single process i

Measure single process j

$$\sigma_{eff} = \frac{\sigma_i \sigma_j}{\sigma_{ij}}$$

Measure processes i and j
in the same event and
from different parton scatterings

- Trivial if we would know that i and j cannot come from the same parton scattering
  - Not the case in practice
- Example: W+2 jet events



- Need experimental handle to distinguish single and double parton scattering

JHEP 03 (2014) 032

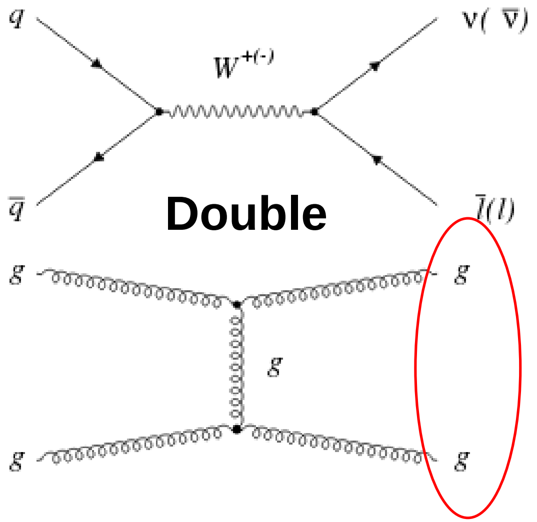
Distinguish single and double parton scattering in W+2 jet events

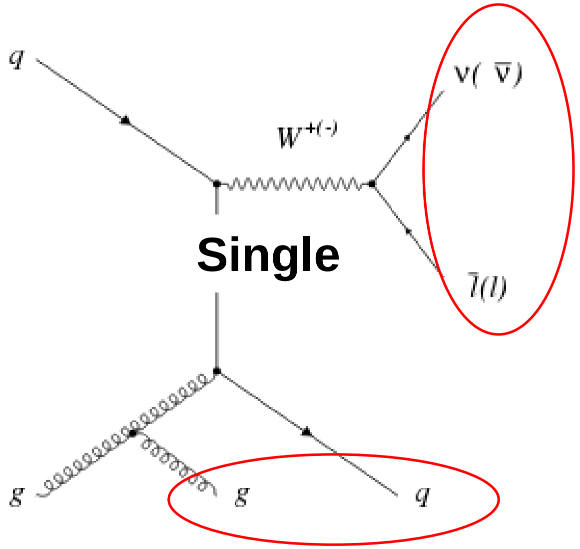
Azimuthal angle between W and dijet

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\mu, \not{E}_T)\cdot\vec{p}_T(j_1,j_2)}{|\vec{p}_T(\mu, \not{E}_T)|\cdot|\vec{p}_T(j_1,j_2)|}\right)$$

ΔS ~ random

W boson and dijet system balance each other → ΔS ~ π





Relative p_T balance

$$\Delta^{rel}\, p_T = \frac{|\vec{p}_T(j_1)+\vec{p}_T(j_2)|}{|\vec{p}_T(j_1)|+|\vec{p}_T(j_2)|}$$

Jets balance each other → Δ^{rel} p_T small

Δ^{rel} p_T large

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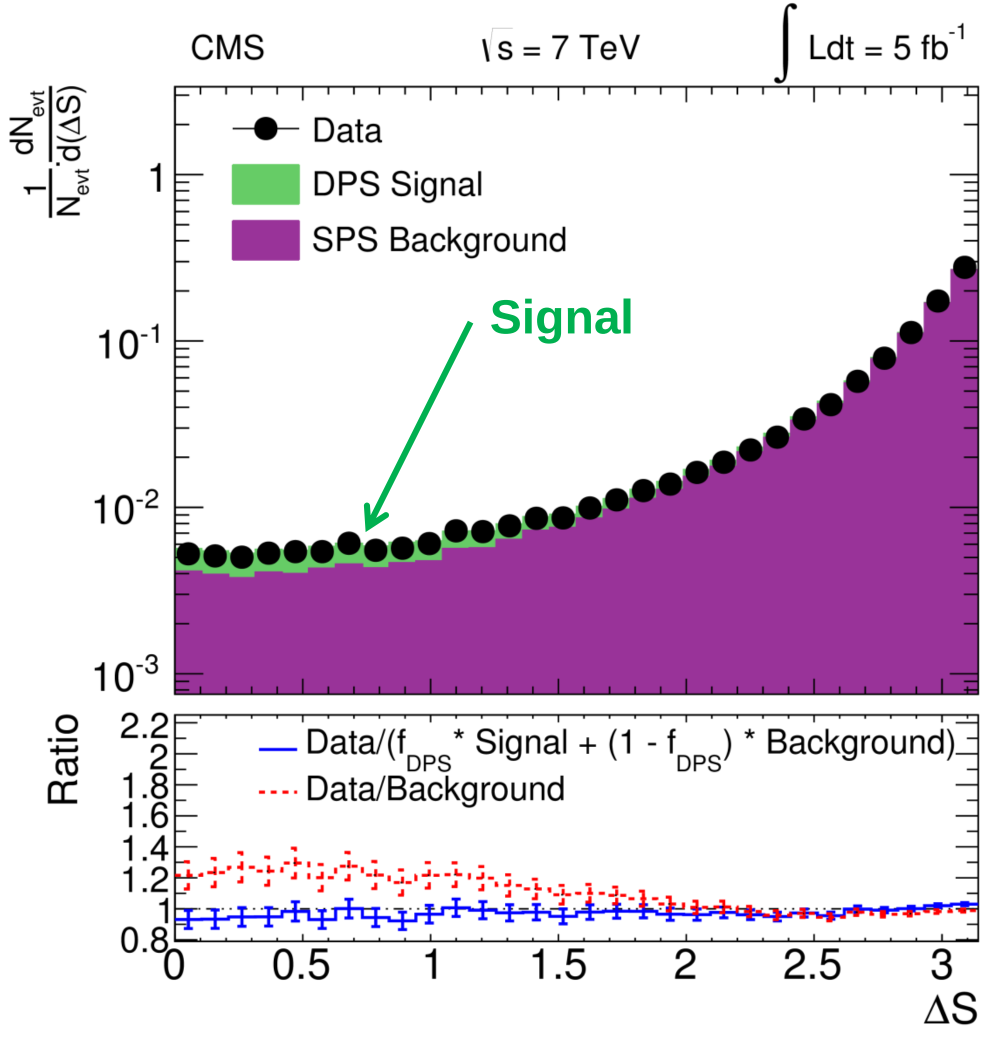
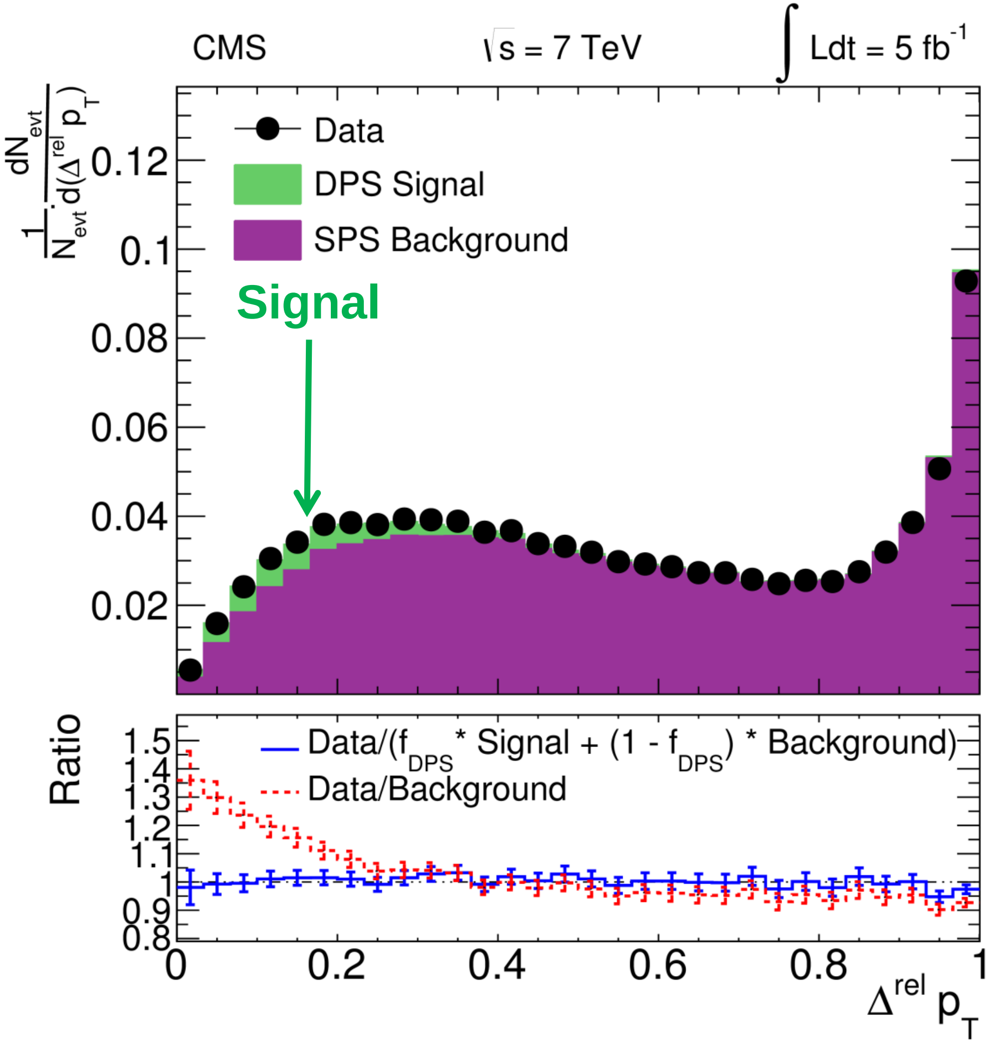
Signal and Background Distributions



Azimuthal angle between W and dijet



Relative p_T balance

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Influence of MPI

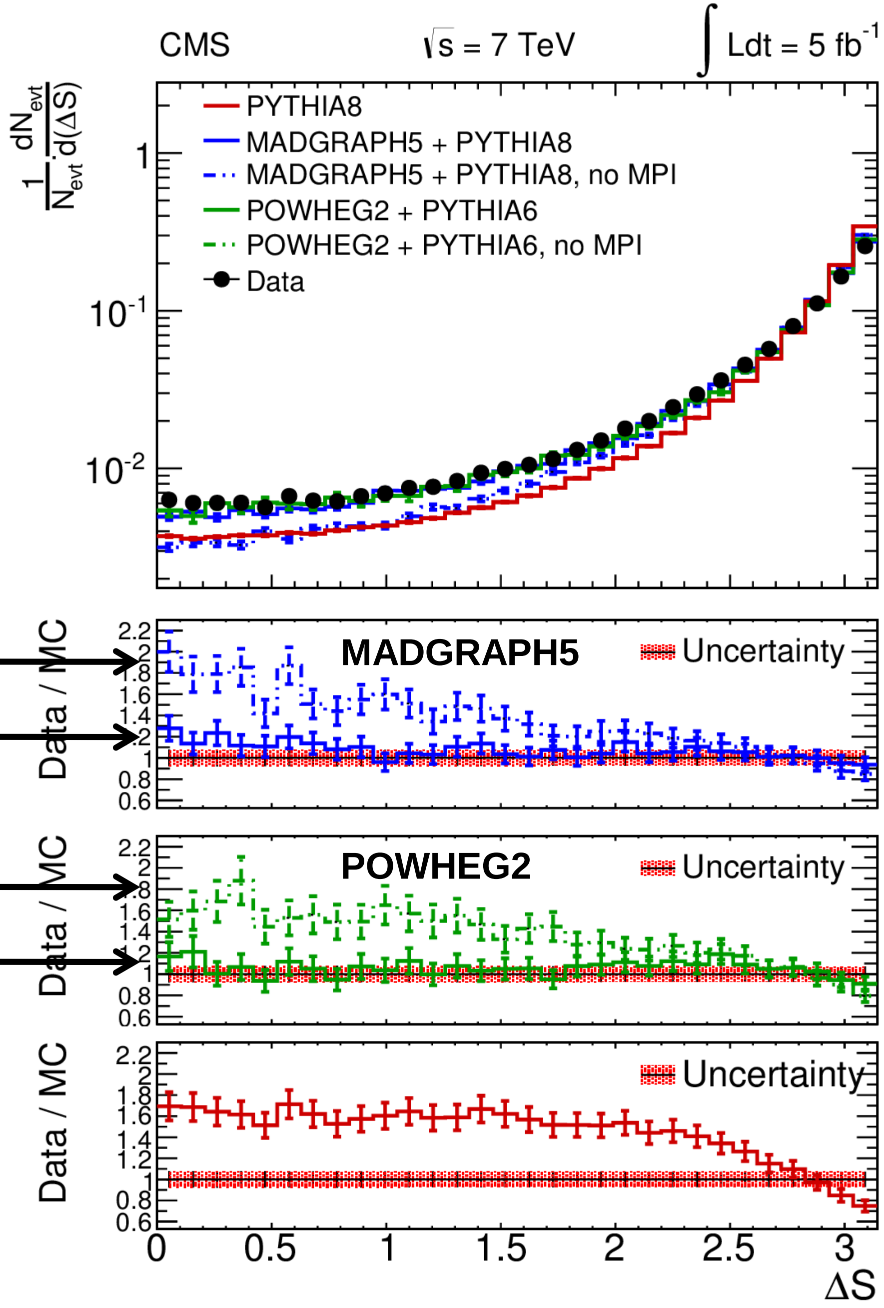
- Correct description of ΔS and $\Delta^{rel}\, p_T$
  - requires higher-order diagrams
  - inclusion of MPI

without MPI

with MPI

without MPI

with MPI



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Extraction Method

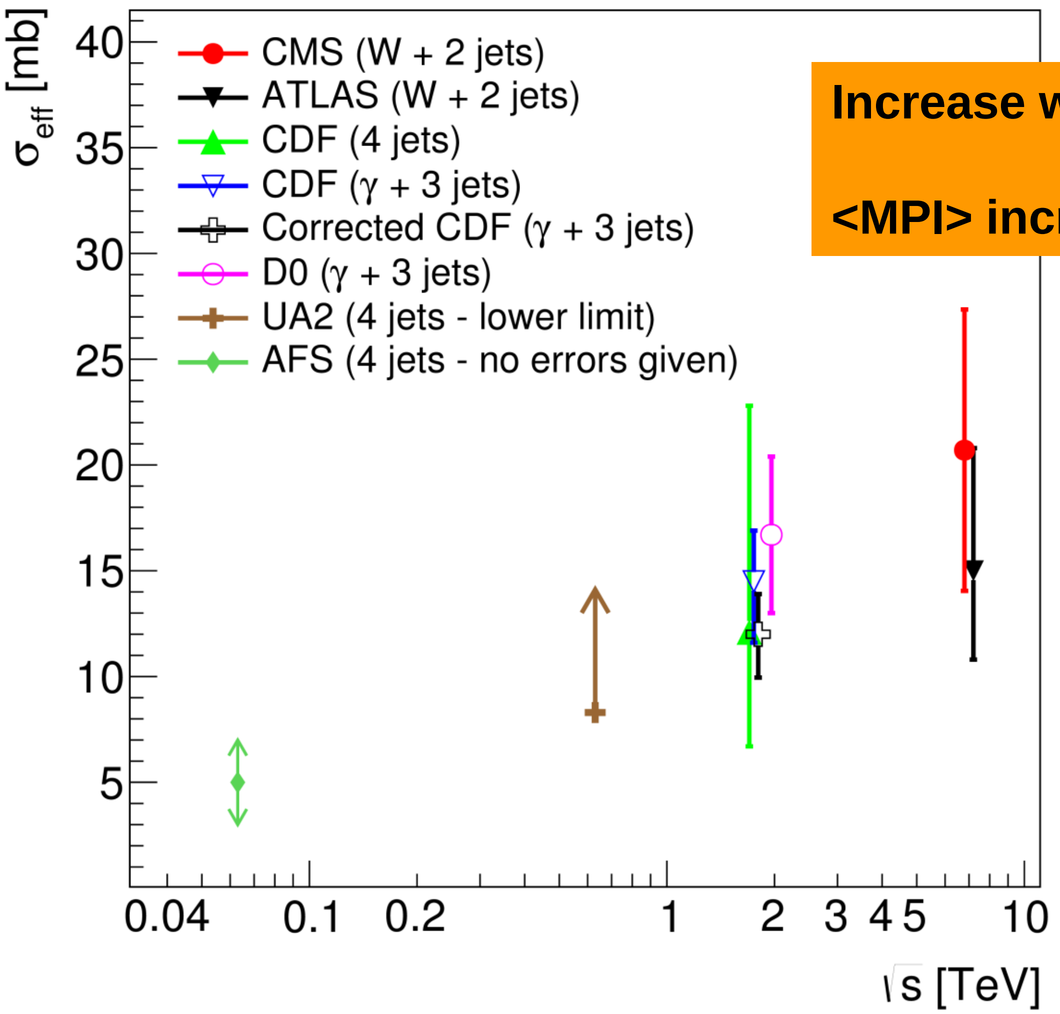
$$\sigma_{eff} = \frac{\sigma_i \sigma_j}{\sigma_{ij}} = \frac{\sigma_{\mathrm{W+0jets}} \sigma_{\mathrm{2jets}}}{\sigma^{\mathrm{DPS}}_{\mathrm{W+2jets}}} = \frac{N_{\mathrm{W+0jets}} \sigma_{\mathrm{2jets}}}{N^{\mathrm{DPS}}_{\mathrm{W+2jets}}} = \frac{R}{f_{\mathrm{DPS}}} \sigma_{\mathrm{2jets}} \longrightarrow \mathbf{0.0409\ mb}$$

$$R = \frac{N_{\mathrm{W+0jets}}}{N_{\mathrm{W+2jets}}} \longrightarrow \mathbf{27.8}$$

$$f_{\mathrm{DPS}} = \frac{N^{\mathrm{DPS}}_{\mathrm{W+2jets}}}{N_{\mathrm{W+2jets}}} \longrightarrow \mathbf{0.055}$$

$\boxed{\boldsymbol{\sigma_{\mathrm{eff}} = 20.7 \pm 0.8\ (\mathrm{stat.}) \pm 6.6\ (\mathrm{syst.})\ \mathrm{mb}}}$

√s Dependence



Increase with √s?

<MPI> increases

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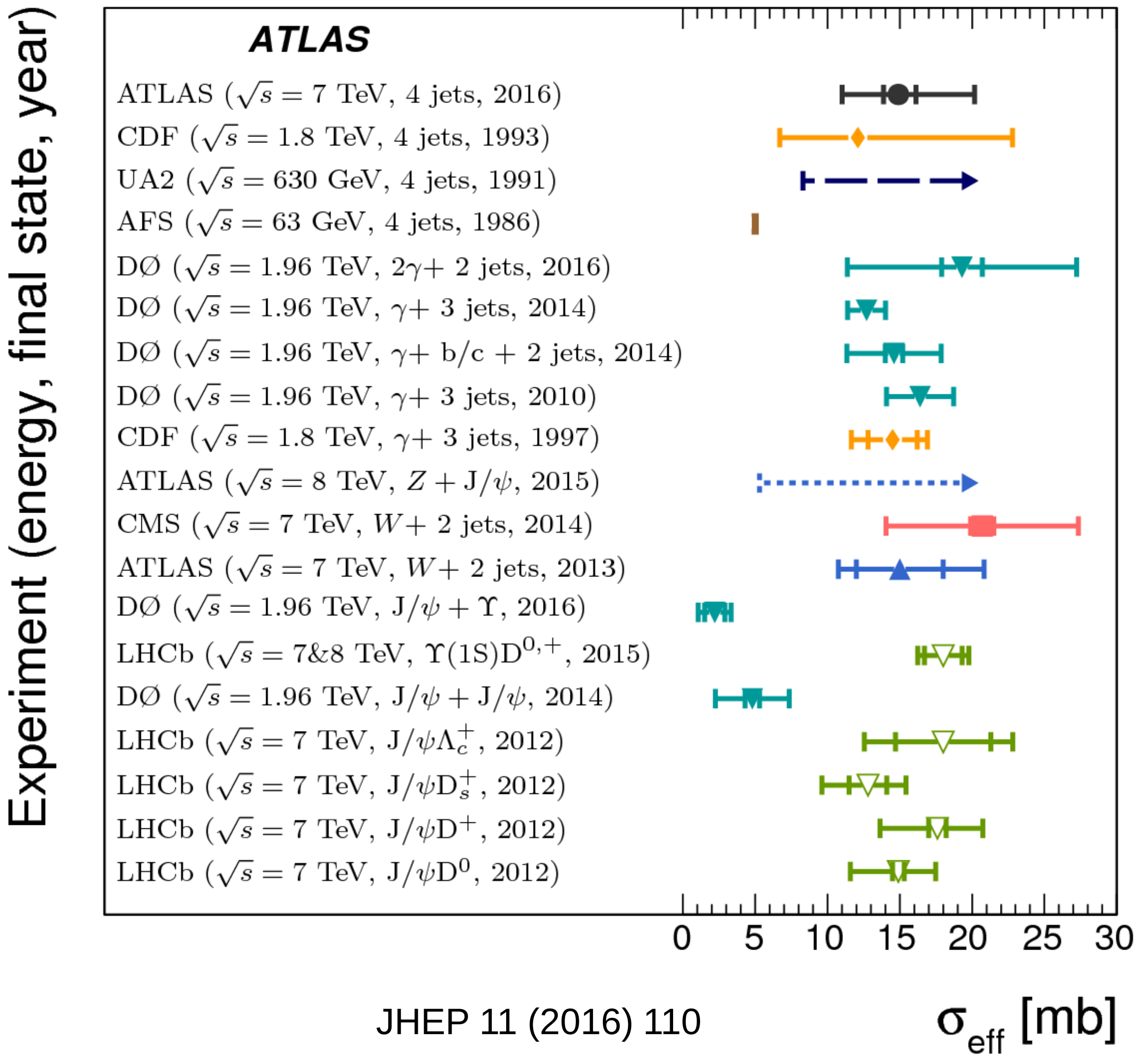

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Summary

Hard Double Parton Scattering

- Double parton scattering measures the probability that two processes occur in the one collision in different parton scatterings
  - Quantified by σ_{eff}
- Irreducible background of higher-order diagrams
  - Diagram contains both processes within one parton scattering

Multiplicity Biases

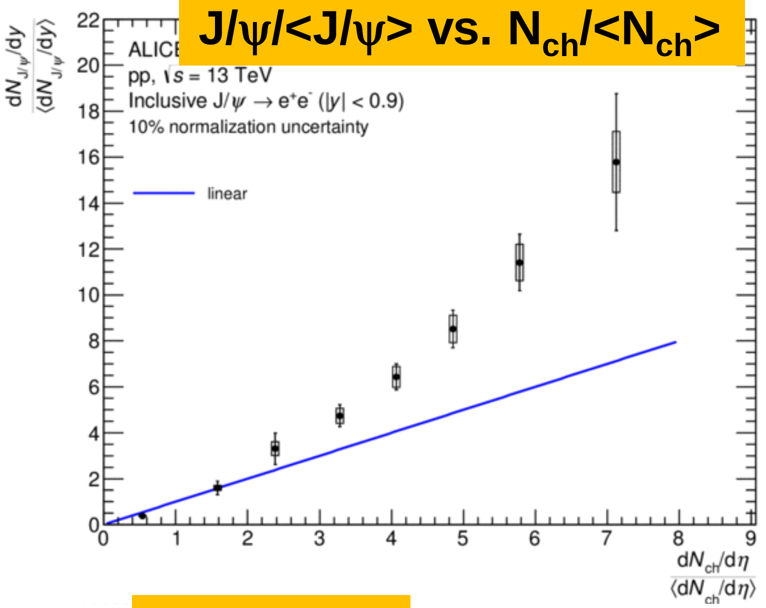
Bias?

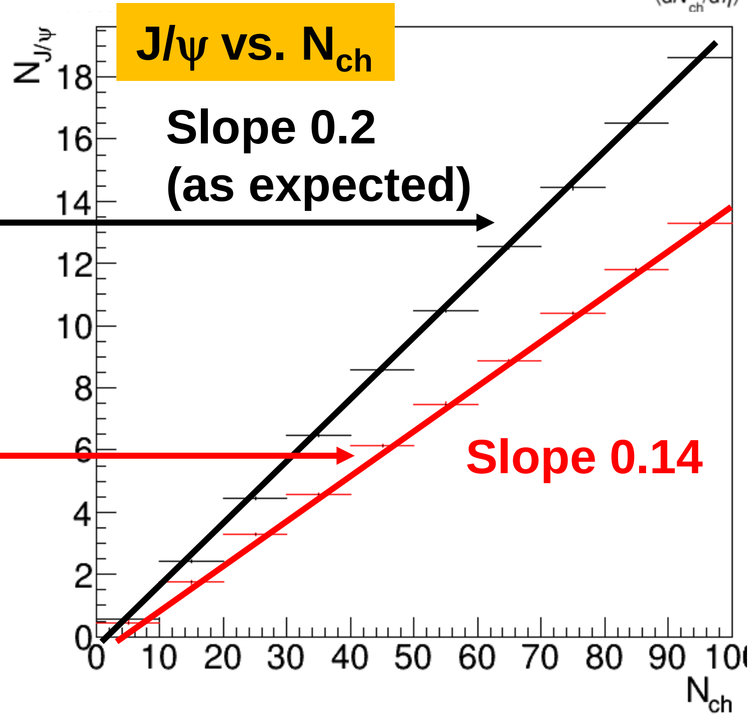
- Many observables measured as a function of multiplicity
- Can we consider the multiplicity independent from the studied process?
  - Independent = only characterization of the event activity
  - Correlation between multiplicity and studied process only indirectly through event activity

- Let’s discuss two aspects
  - What biases can occur when multiplicity is used to slice events into classes
  - How are these biases related to MPI

Bias!

- We discussed J/ψ vs. N_{ch} measurement
- Imagine simple (unphysical) picture
  - Random number of particles
  - Per particle probability of producing J/ψ is 20%
  - Variant: Per produced J/ψ add 2 particles
  - Slope drastically changed

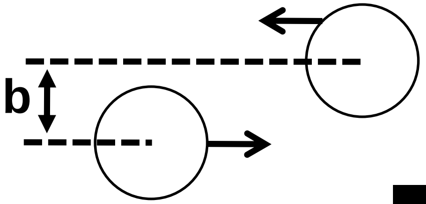




Concept: Centrality

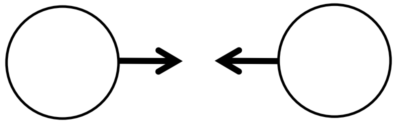
Short excursion
to heavy-ion physics

- Overall activity and multiplicity depends on nuclear overlap



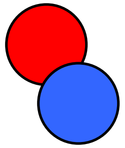
Peripheral
b > 0

Central
b = 0



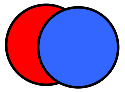
Striking relation between b and multiplicity

Low multiplicity → **High multiplicity**



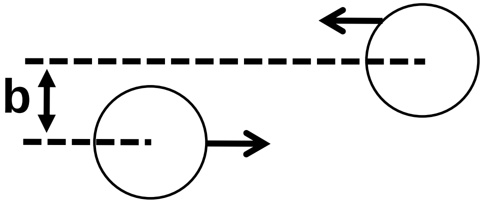
Centrality defined in 0-100%

100% most peripheral **0% most central**

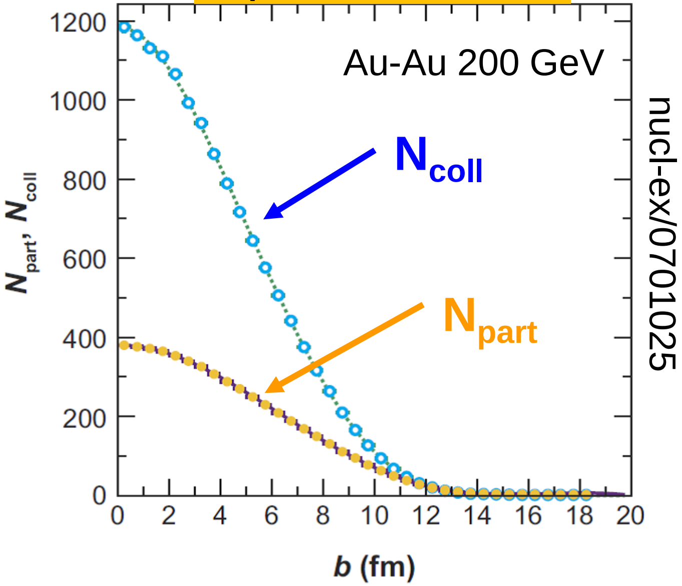


Large Systems: Pb-Pb

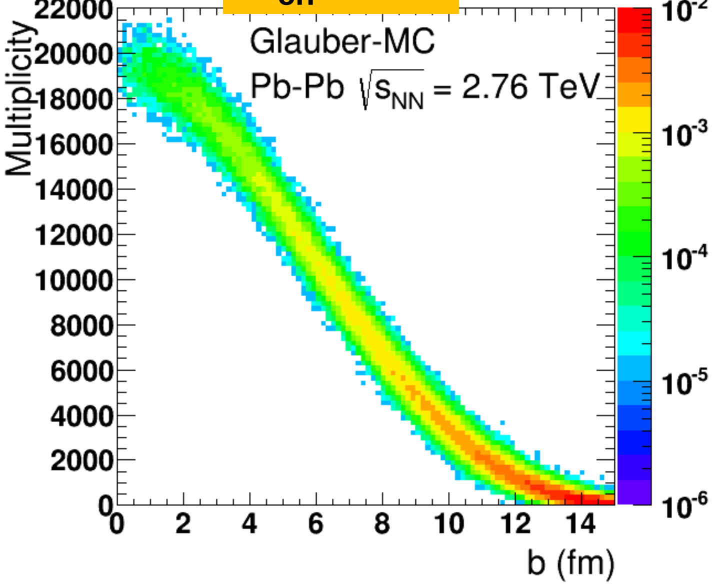
- Multiplicity depends on participants nucleons N_{part}
  - N_{part} depends on collision impact parameter b
- Clear correlation between multiplicity and b
- Correlation correlated across phase space



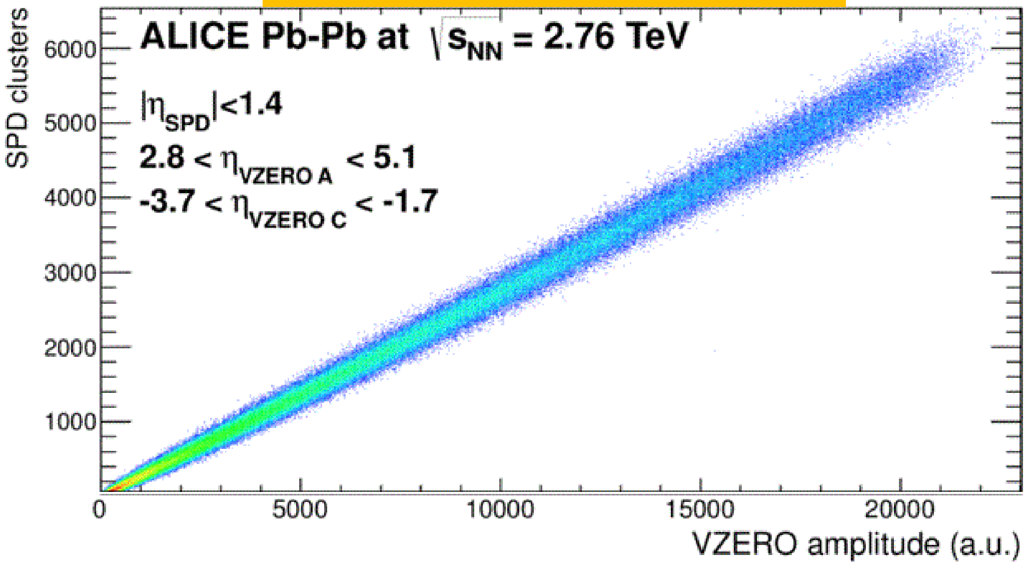
N_{part}, N_{coll} vs. b



N_{ch} vs. b



Central vs. forward N_{ch}



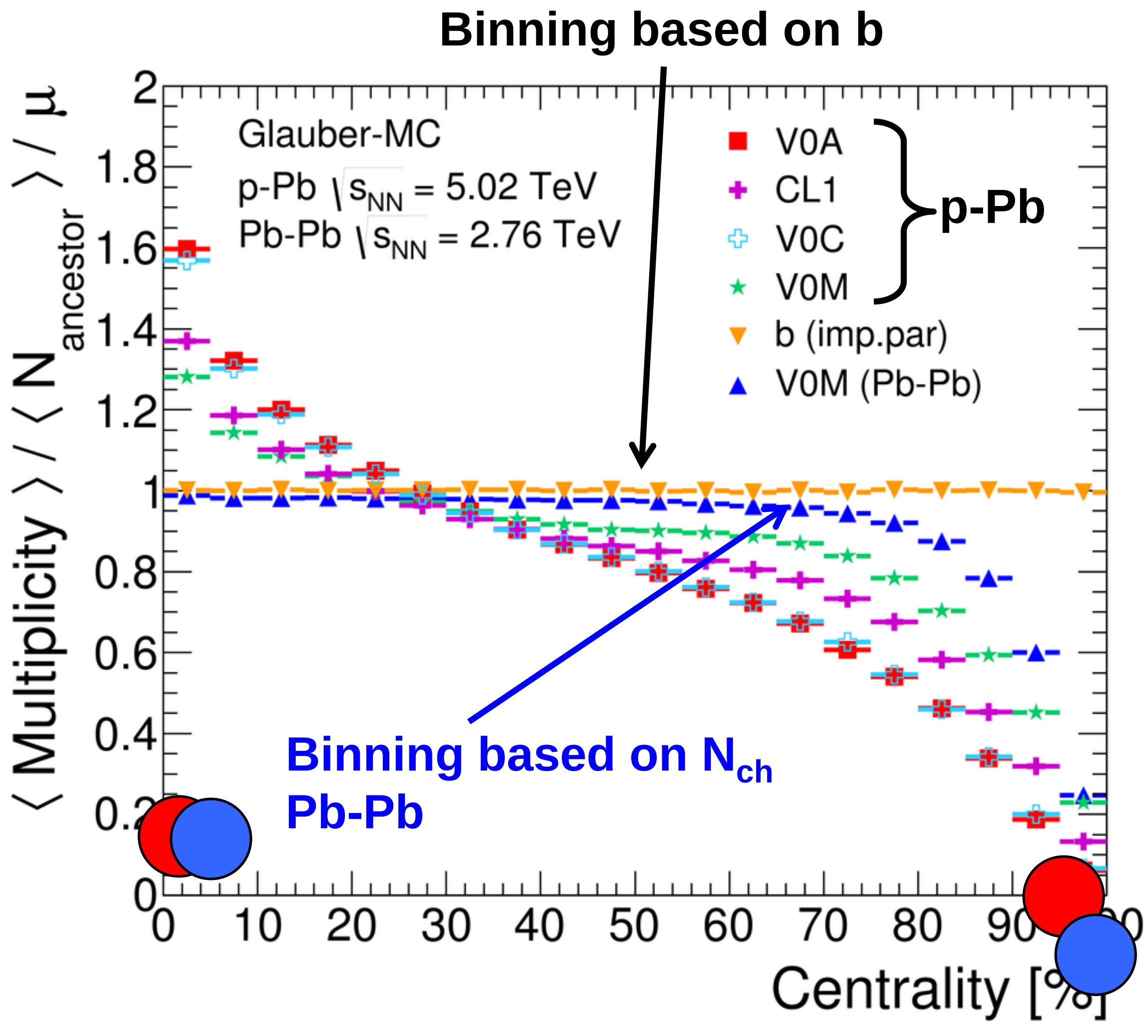
Large Systems: Pb-Pb

- Can the multiplicity stemming from each N_{part} be treated independently?
- Tested within Glauber model

$$\frac{N_{ch} / N_{part}}{\mu}$$

μ = average per N_{part}
[in Glauber: <N_{ch}> per NBD]

- Binning in b → unity
- Binning in N_{ch}
  - Unity for 0-70% centrality
  - Deviations for the 30% lowest multiplicity
- So called *multiplicity bias*



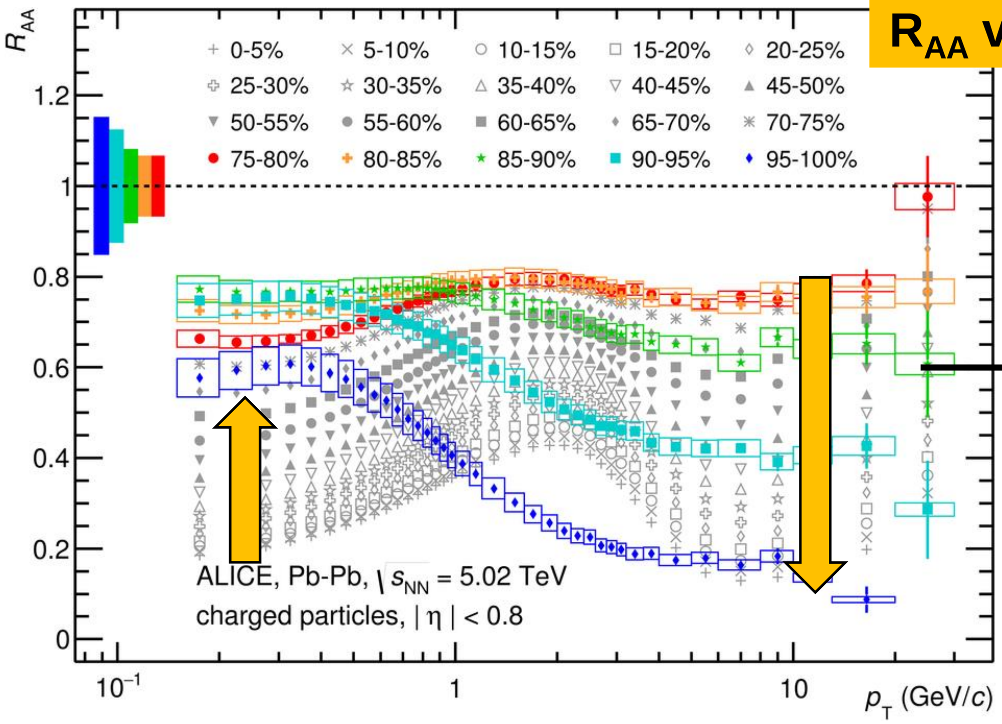
Phys. Rev. C 91 (2015) 064905

Consequence: R_{AA} in peripheral Pb-Pb

- Nuclear modification factor R_{AA} commonly used to quantify energy loss in the Quark-Gluon Plasma
- Multiplicity bias distorts signal in peripheral collisions
- Above 80% centrality, R_{AA} decreases due to bias

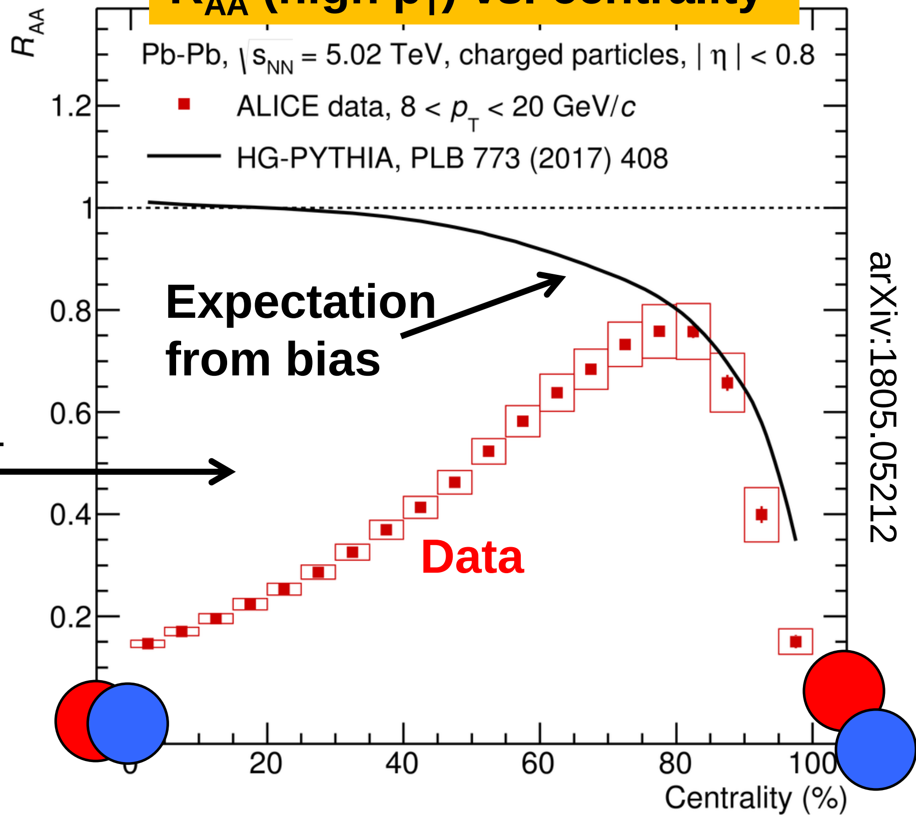
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

R_{AA} vs. p_T



at high p_T

R_{AA} (high p_T) vs. centrality

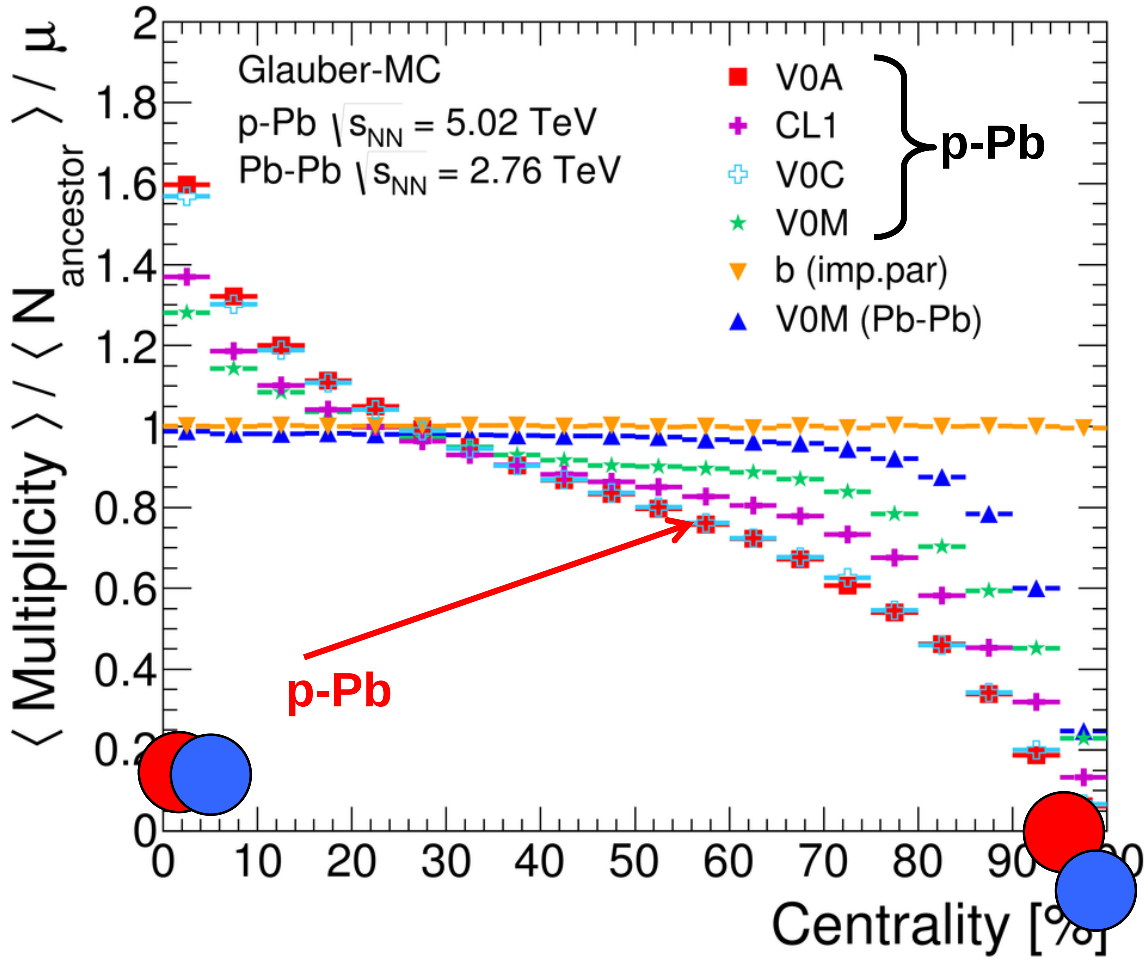


arXiv:1805.05212

Intermediate Systems: p-Pb

- Less participating nucleons
  → larger biases
  (8 in p-Pb vs. 110 in Pb-Pb)

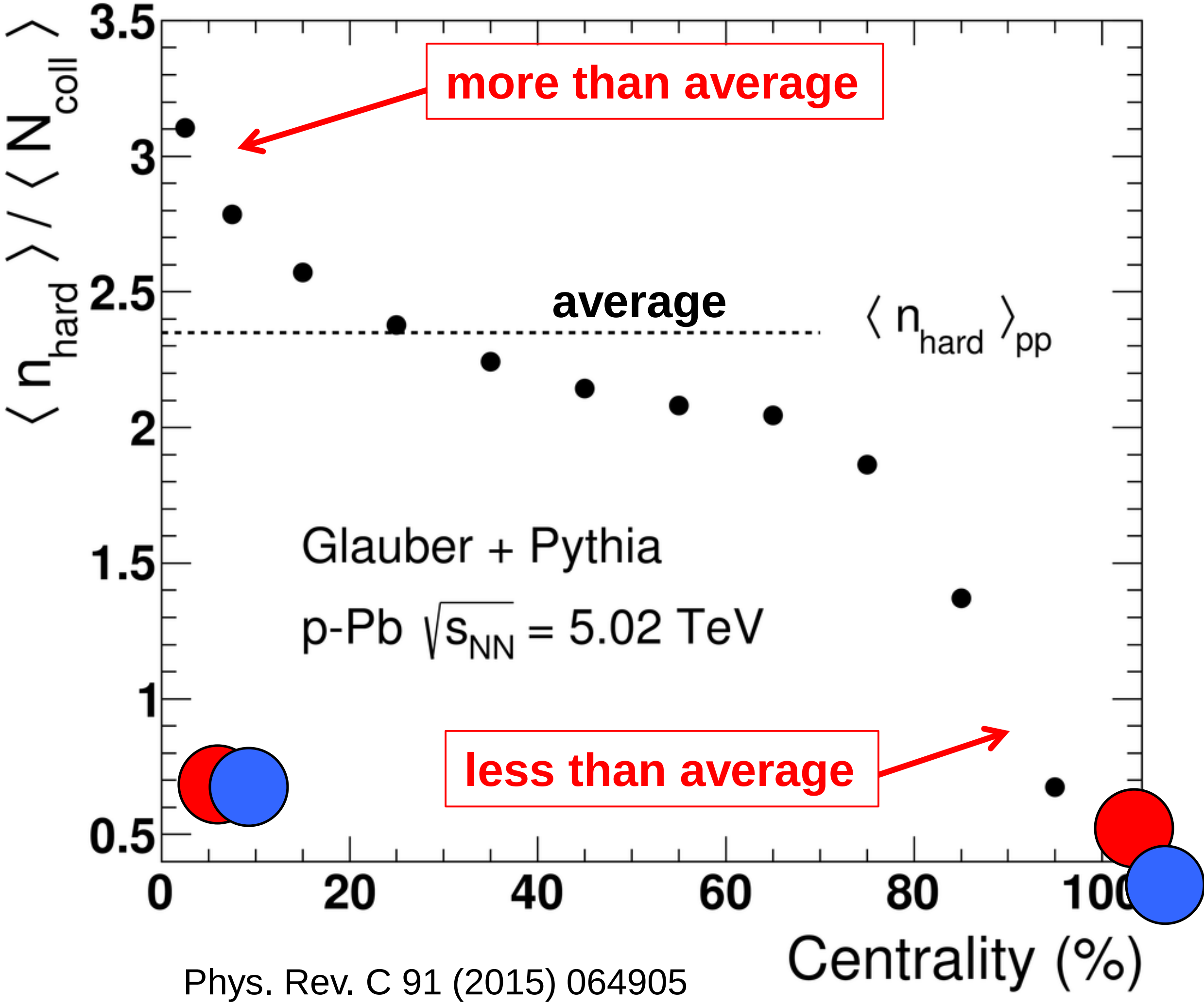
- Multiplicity bias at all centralities



Phys. Rev. C 91 (2015) 064905

Intermediate Systems: p-Pb

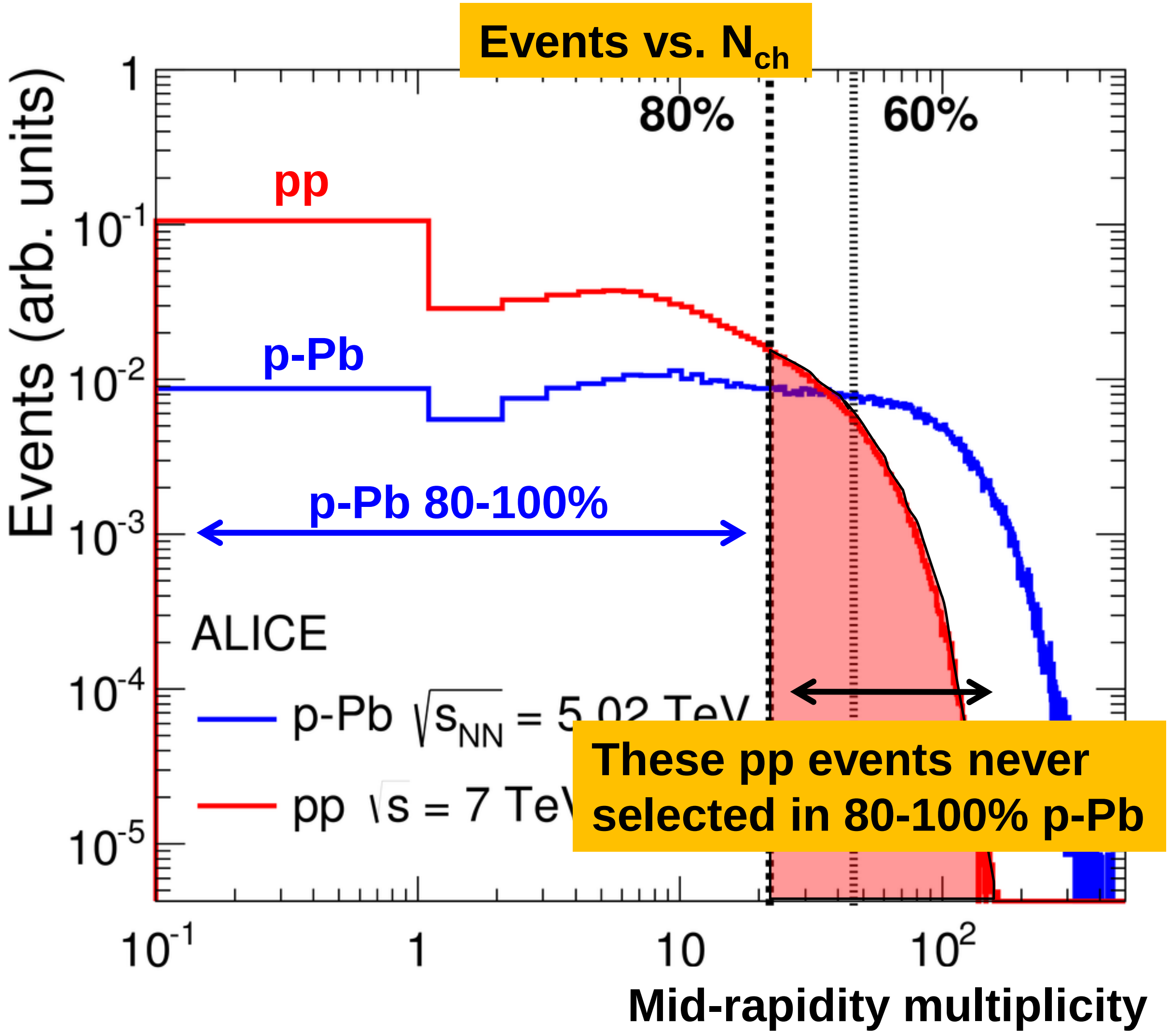
- Couple Glauber and PYTHIA
- Calculate #MPI per NN collision
- Significant deviations from average
- Clear bias
  → bias on N_{ch}, hard yields, …



Phys. Rev. C 91 (2015) 064905

Intermediate Systems: p-Pb

- High p_T particles are produced only in high Q^2 processes
  - High Q^2 → high N_{ch} (on average)
  - Introduces trivial correlation
- Low multiplicity selections are depleted of such processes
  - High p_T yields reduced at low N_{ch}
- *Jet-veto bias*

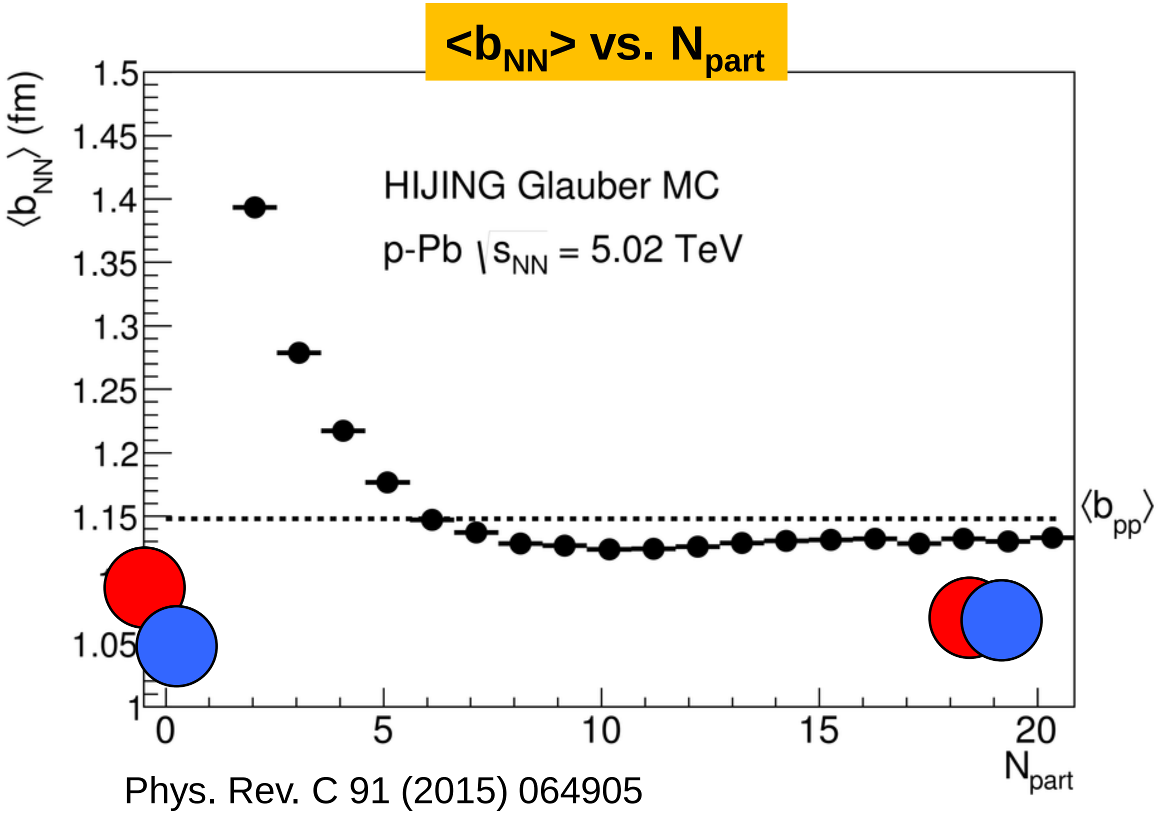


Phys. Rev. C 91 (2015) 064905

Intermediate Systems: p-Pb

- Nucleon-nucleon impact parameter b_{NN}
  - Increases in peripheral collisions → less MPI
  - Decreases in central collisions → more MPI

Geometrical bias



Phys. Rev. C 91 (2015) 064905

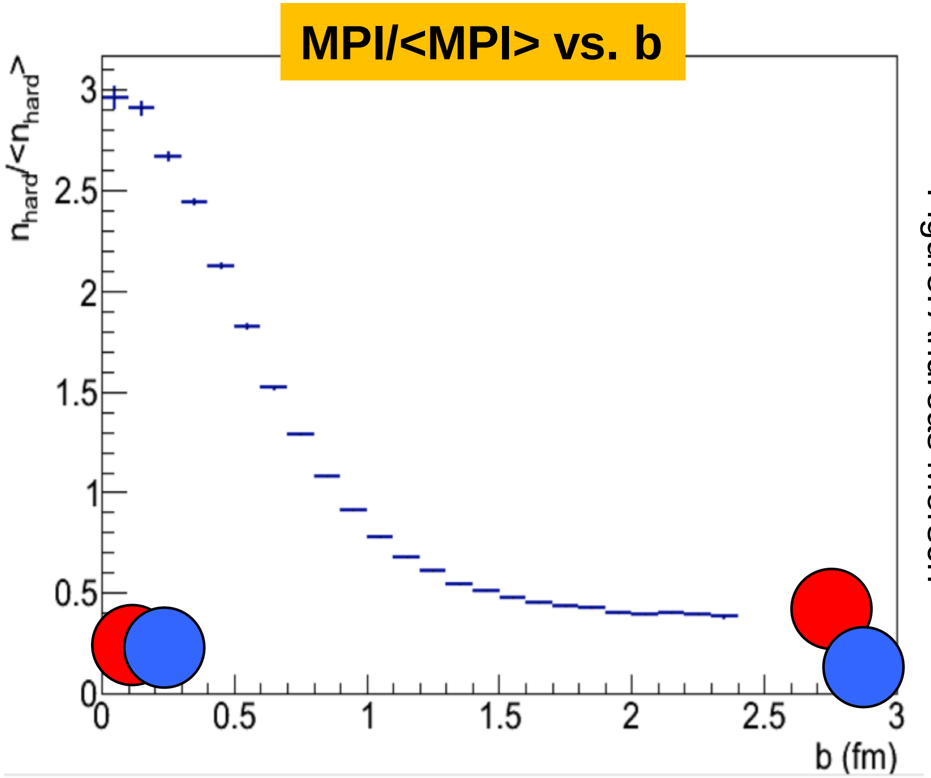


Figure: Andreas Morsch

Consequence: R_{pA} in p-Pb

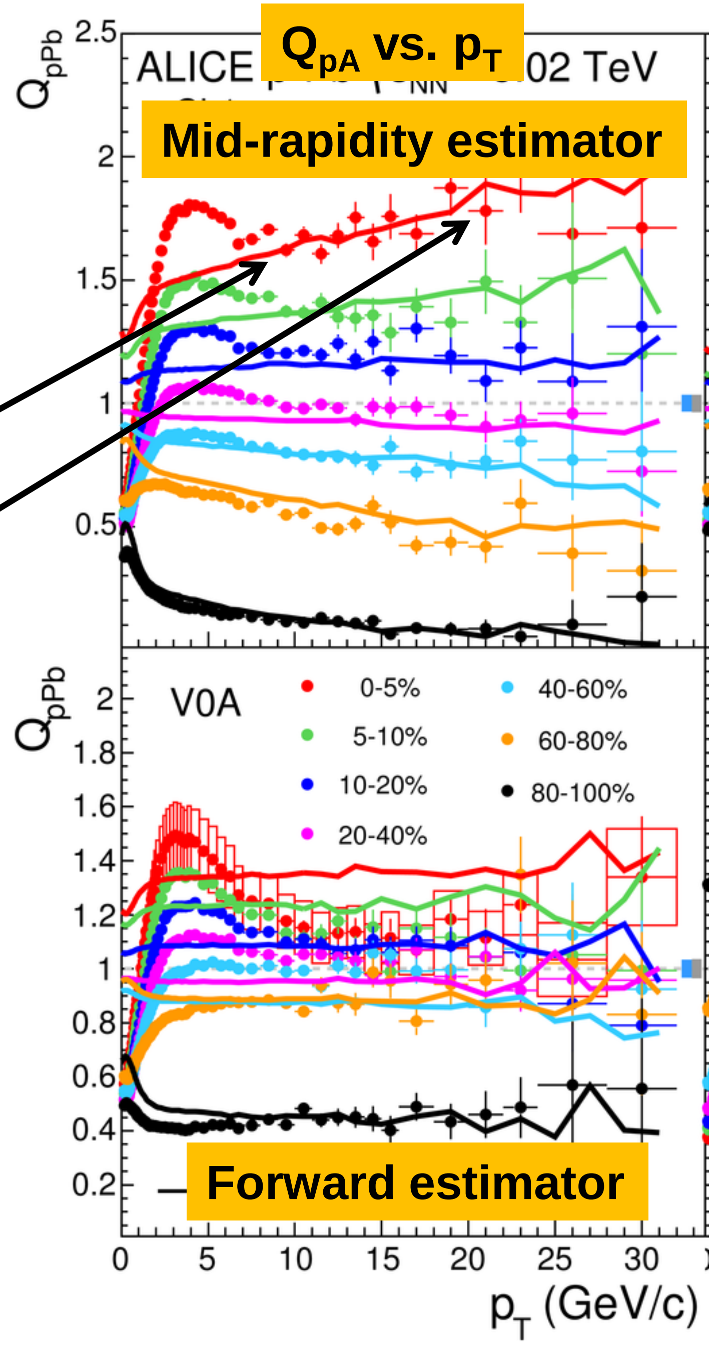
- R_{pA} usually sensitive to energy loss
  - Distorted by these biases

- Effect depends on centrality estimator used
  - The larger the separation between estimator and measurement, the smaller the biases

- No measurement without considering these biases
  - Due to estimator dependence R_{pA} renamed to Q_{pA}

Model estimating bias

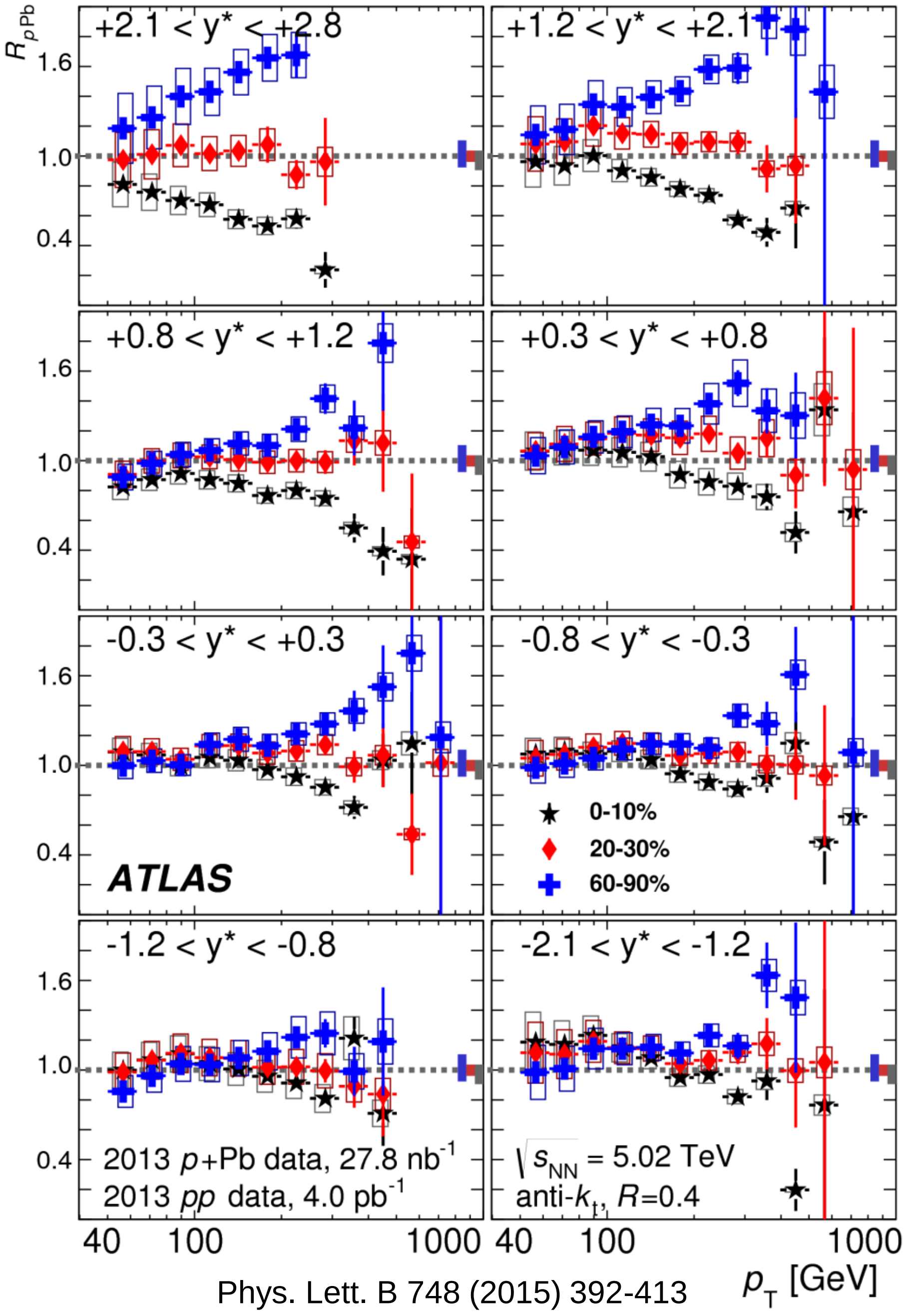
Data



Phys. Rev. C 91 (2015) 064905

Consequence: R_{pA} in p-Pb

- Similar bias for RpA of reconstructed jets
- Rapidity dependence clearly visible

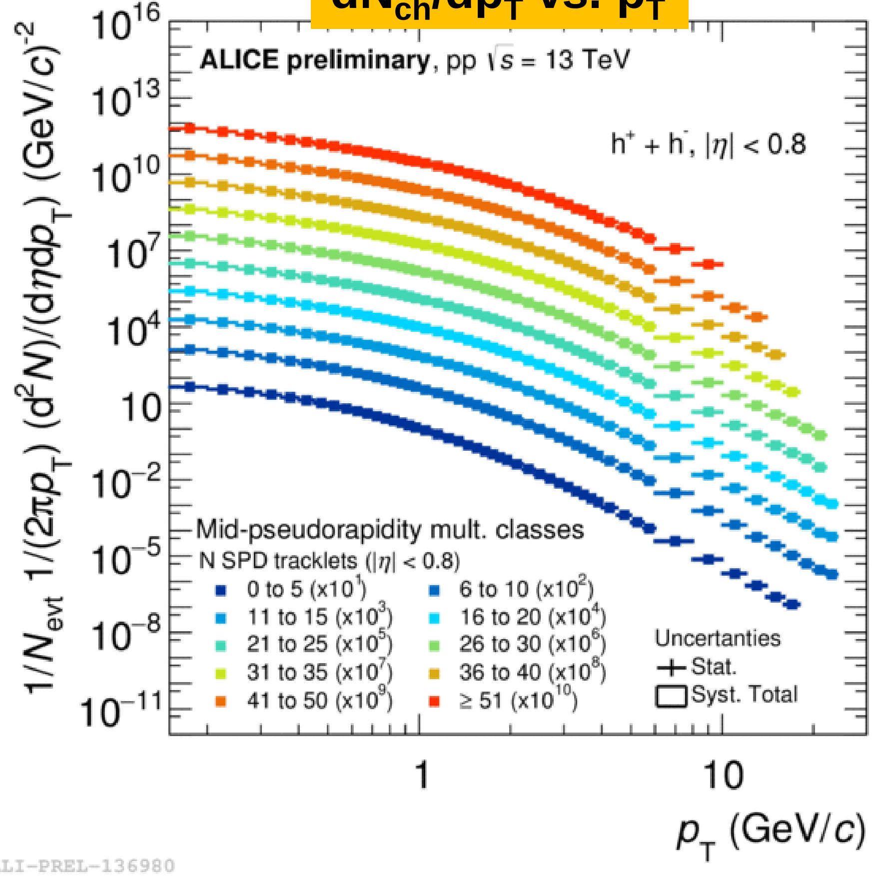


Phys. Lett. B 748 (2015) 392-413

Small Systems: pp

- Charged-particle spectra in multiplicity bins

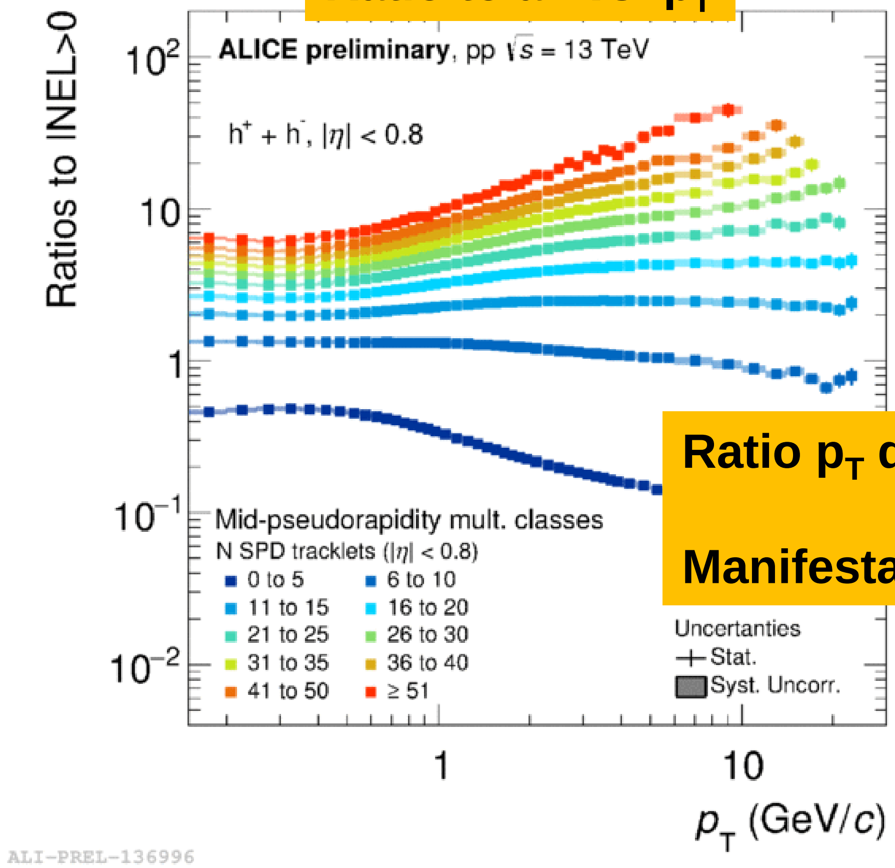
dN_{ch}/dp_T vs. p_T



Large N_{ch}

Low N_{ch}

Ratio to all vs. p_T

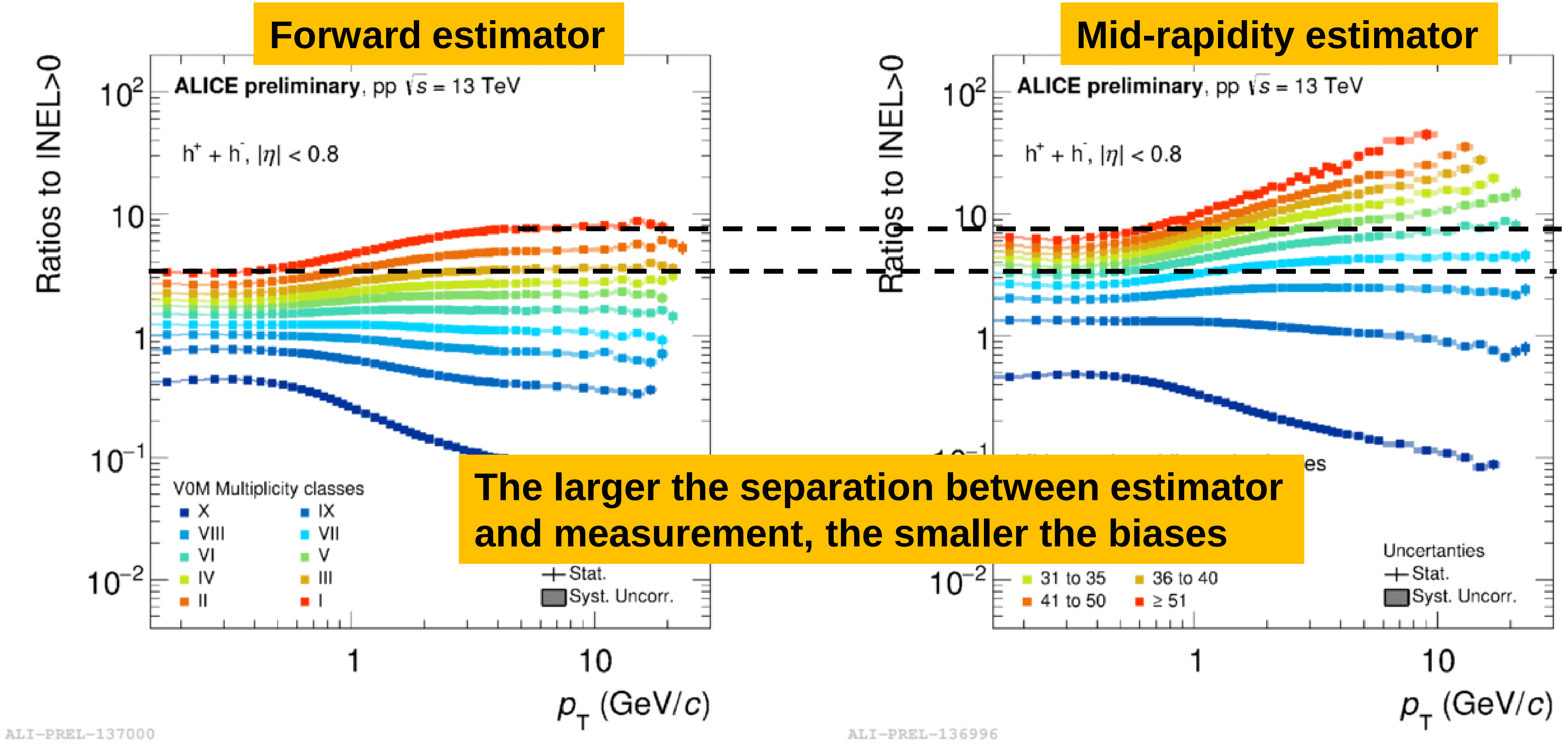


Ratio p_T dependent

Manifestation of jet-veto bias

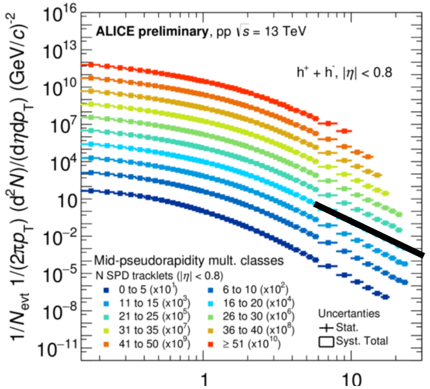
Small Systems: pp

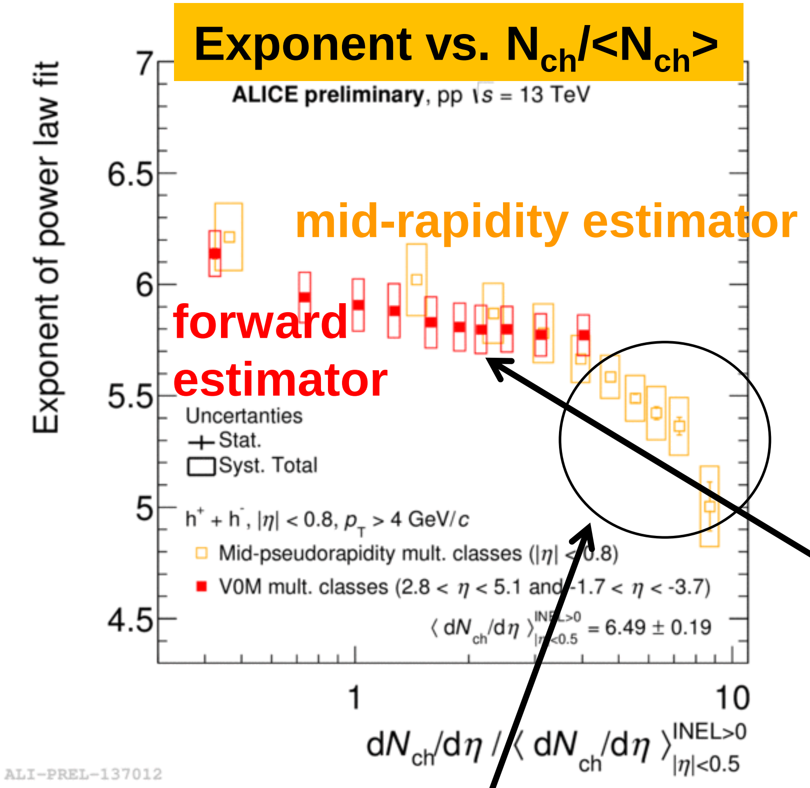
- Charged-particle spectra in multiplicity bins



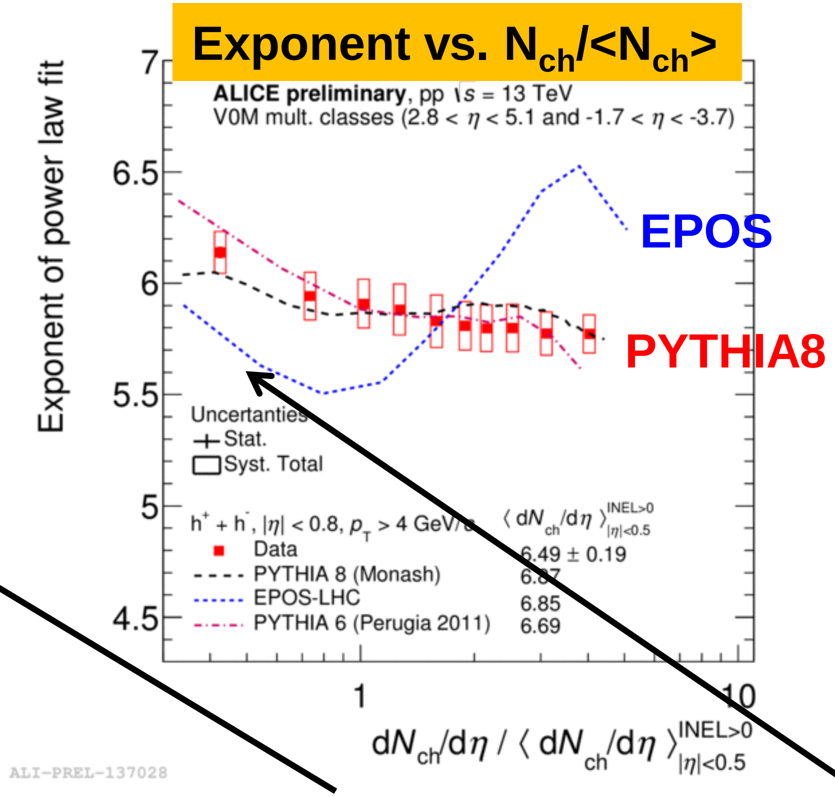
Small Systems: pp

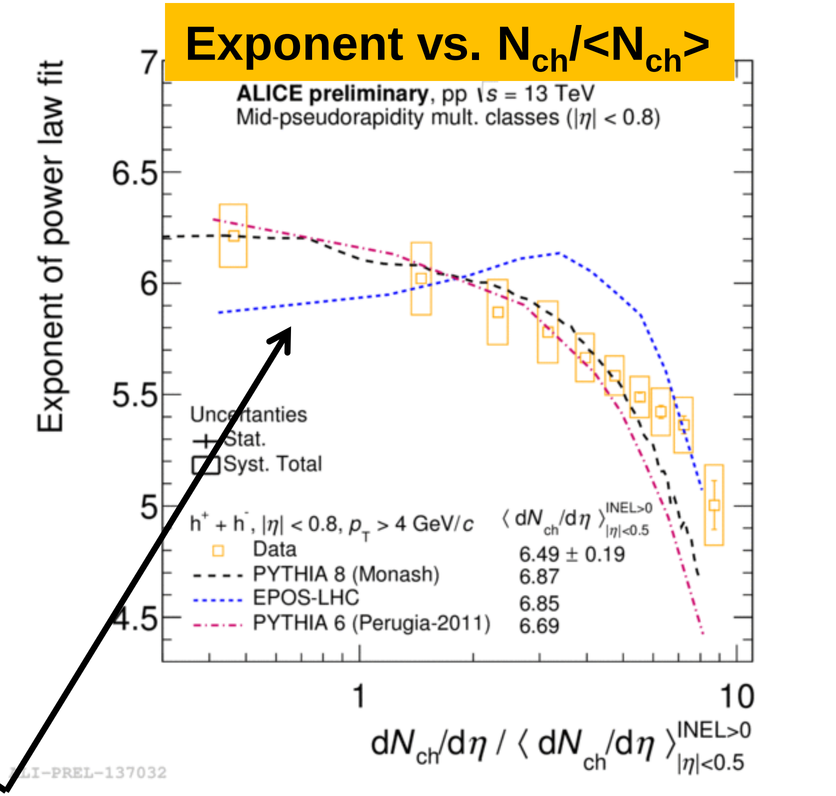
- What is the high p_T shape evolution?
  - Quantified by power-law fit above 6 GeV/c





Dynamic range

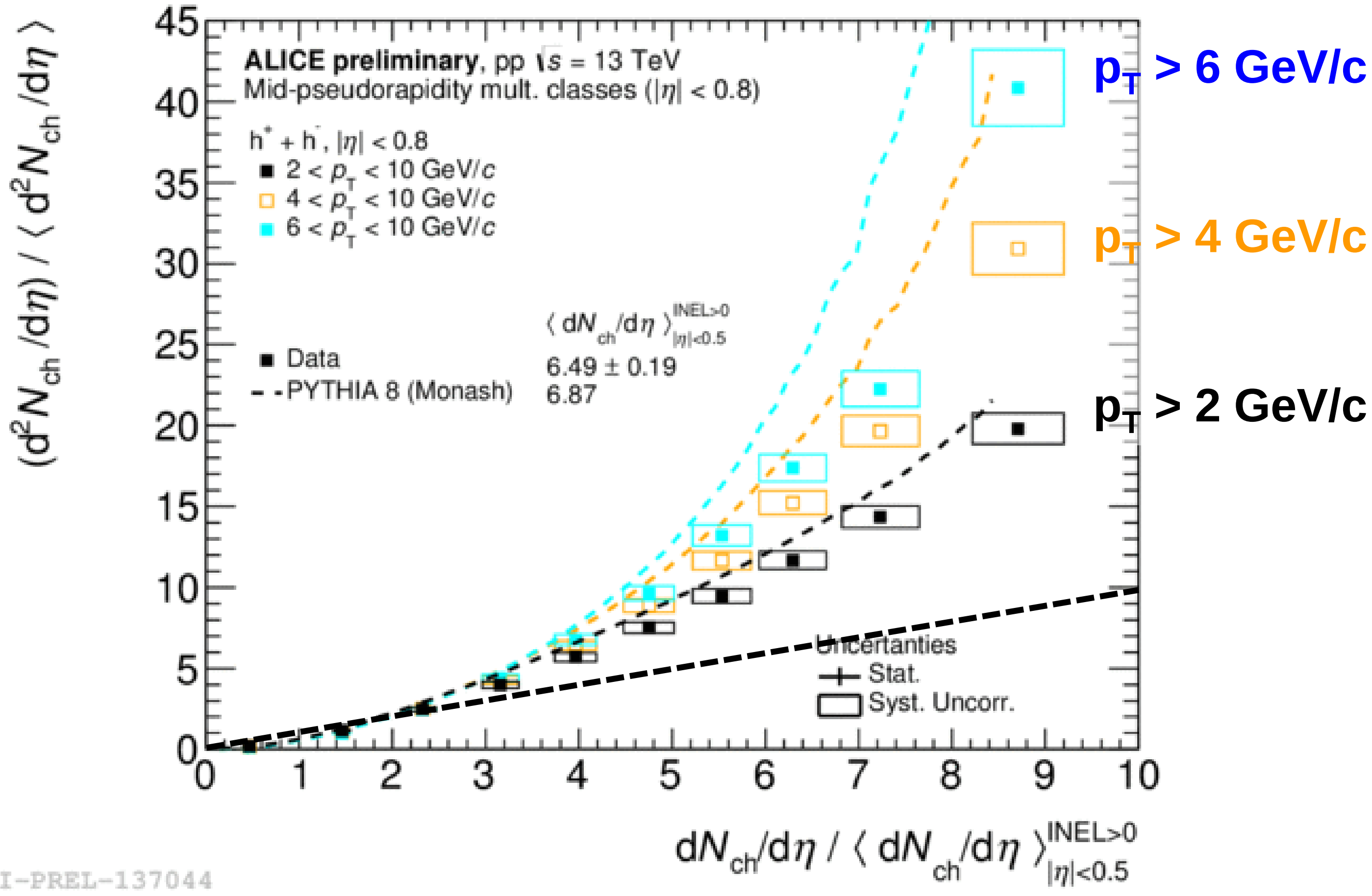




Similar exponent in data … not necessarily in MC

Small Systems: pp

- How do the high p_T yield scale with multiplicity?



- Significant growth
  - The larger the larger the p_T

Summary

Multiplicity Biases

- Characterization of event activity with multiplicity is biased
  - Multiplicity bias, e.g. when desiring a selection in impact parameter but using multiplicity
  - Geometric bias, e.g. when high-multiplicity collisions select smaller-than-average nucleon-nucleon impact parameter
  - Jet-veto bias, e.g. low multiplicity disfavours large Q^2 processes

- In large systems like Pb-Pb present in peripheral collisions
- In medium systems like p-Pb present in all event classes
- In pp collisions omnipresent and crucial for interpretation

Collective Phenomena

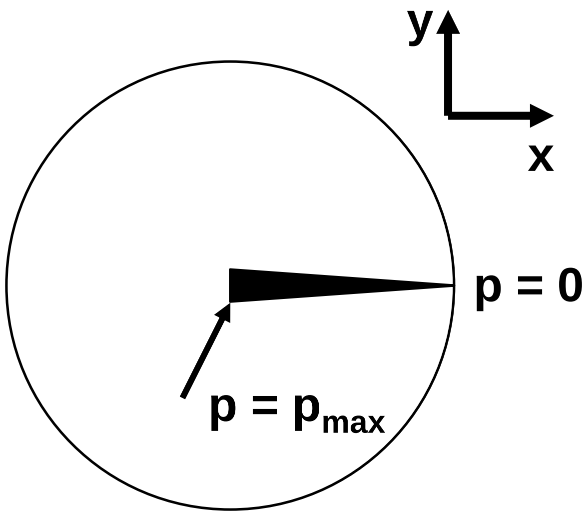
Expansion

Short excursion to heavy-ion physics

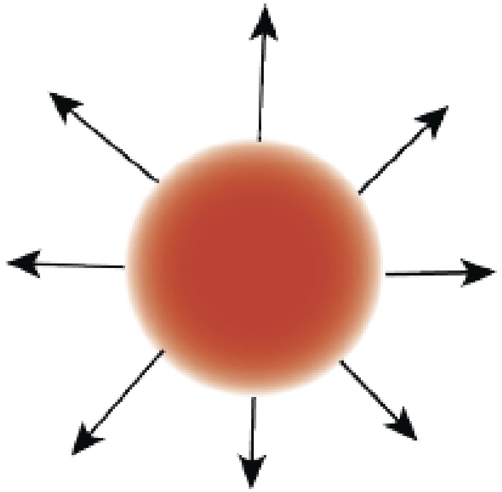
- After collision, QGP droplet in vacuum
- Energy density very high
- Strong pressure gradient from center to boundary

- Consequence: rapid expansion ("little bang")
- Partons get pushed by expansion
  → Momentum increase

- Measurable in the transverse plane (p_T)
  – Called *radial flow*



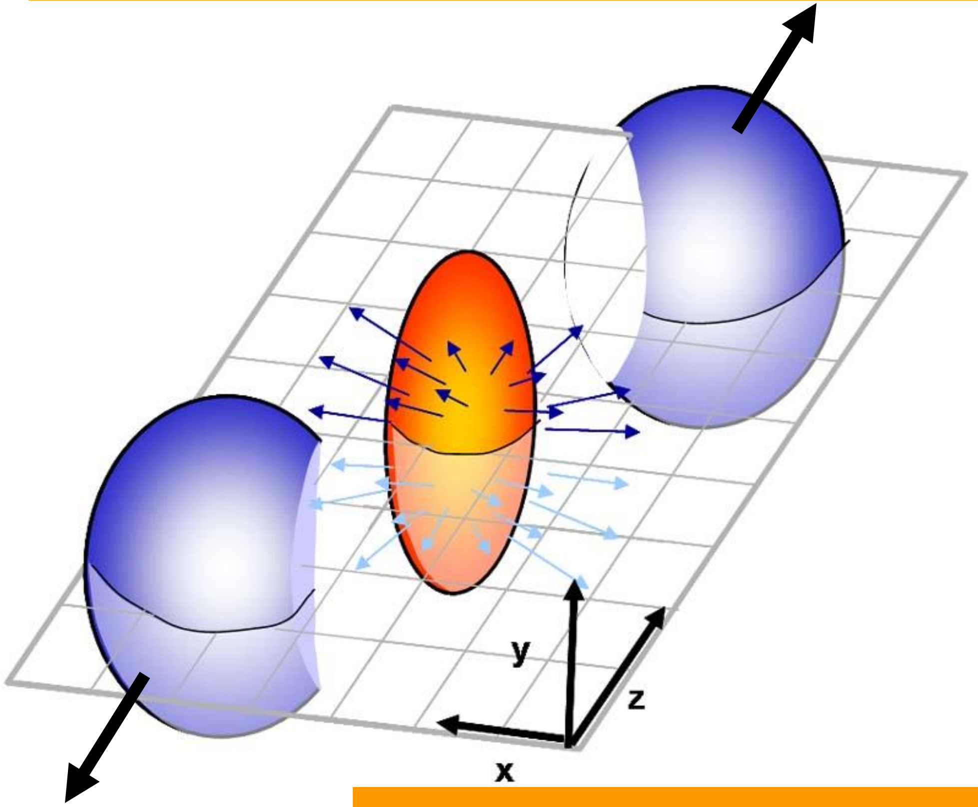
view in beam direction



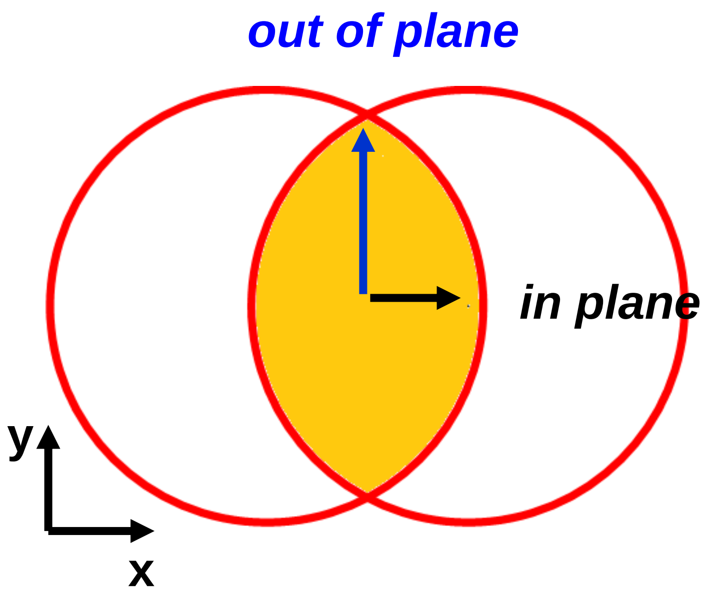
Elliptic Flow

Short excursion
to heavy-ion physics

Overlap of colliding nuclei not isotropic in non-central collisions



Defines *reaction plane* Ψ_{RP}
(spanned by beam axis
and impact parameter vector)



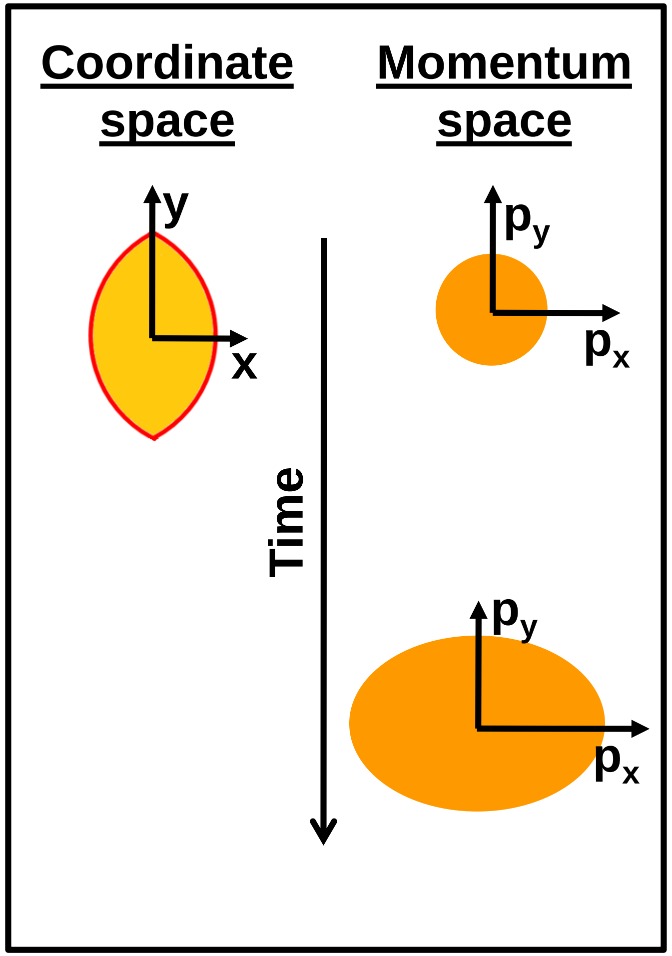
→ Pressure gradients dependent on direction

here: $\frac{dp_x}{dL} > \frac{dp_y}{dL}$

Anisotropy

Short excursion to heavy-ion physics

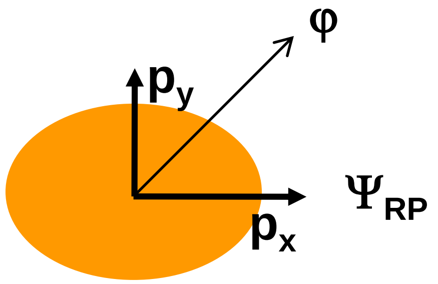
- Spatial anisotropy (almond shape)
  - Quantified by eccentricity $\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$
- Pressure gradient larger in-plane
- Pressure pushes partons
  - More in in-plane than out-of-plane
- Spatial anisotropy converts into momentum-space anisotropy
  - "Faster" particles in-plane
  - Measurable in the final state!



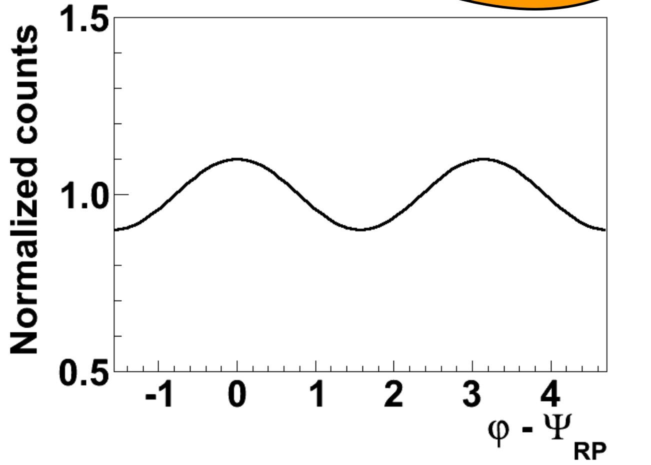
Experimental Signal

Short excursion to heavy-ion physics

- Particles as a function of $\varphi - \Psi_{RP}$

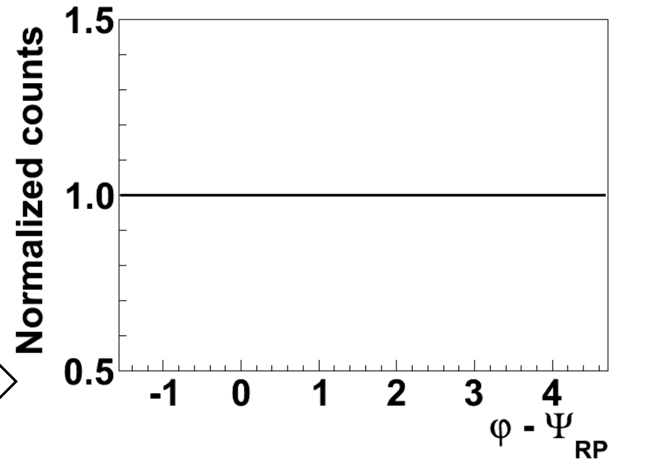


$$\frac{dN}{d\varphi} = A\left(1 + 2v_2 \cos 2(\varphi - \Psi_{RP})\right)$$



- Define $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$
  - Second coefficient of Fourier expansion

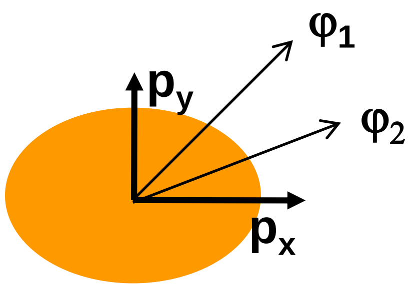
- Ψ_{RP} common *symmetry plane* (for all particles)
- What if there were no correlations with Ψ_{RP}?



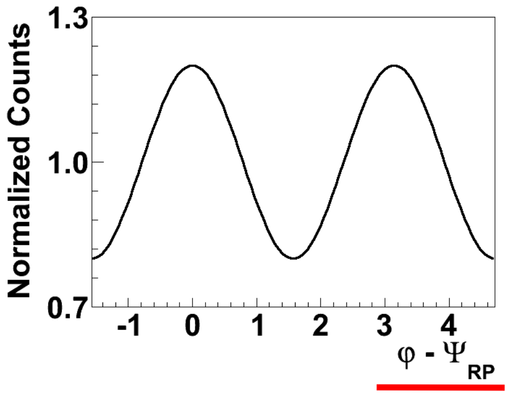
Two-Particle Correlations

Short excursion to heavy-ion physics

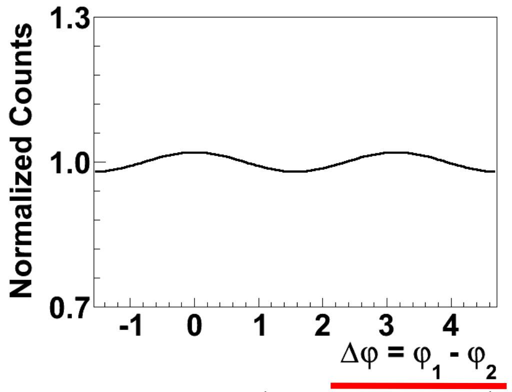
- Rewrite $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$ as $v_2 = \langle e^{i2(\varphi - \Psi_{RP})} \rangle$
- Reaction-plane estimation can be experimentally tricky
- v_2 can also be measured from 2-particle correlations



$$\langle e^{i2(\varphi_1 - \varphi_2)} \rangle = \langle e^{i2(\varphi_1 - \Psi_{RP} - (\varphi_2 - \Psi_{RP}))} \rangle = \langle e^{i2(\varphi_1 - \Psi_{RP})} \rangle \langle e^{i2(\varphi_2 - \Psi_{RP})} \rangle = \boxed{v_2^2}$$



$$v_2 = \langle e^{i2(\varphi - \Psi_{RP})} \rangle$$

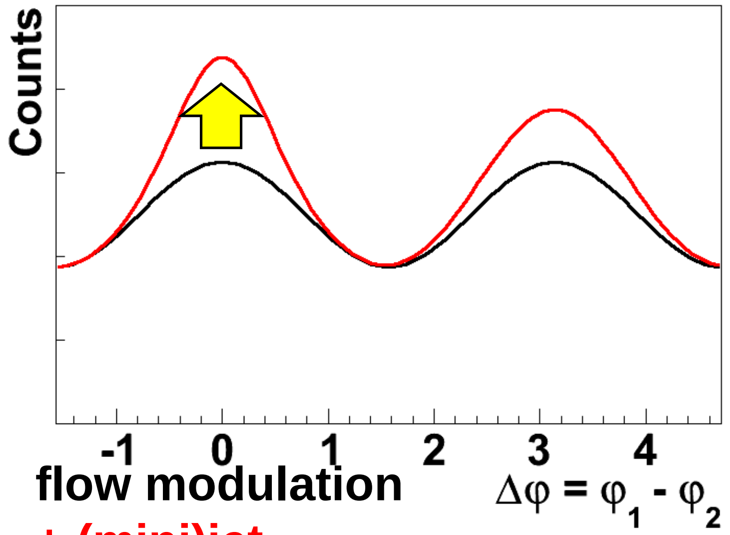


$$v_2^2 = \langle e^{i2(\varphi_1 - \varphi_2)} \rangle$$

Modulation smaller due to $v_2 \rightarrow (v_2)^2$ but statistical power similar

2D Two-Particle Correlations

- Flow component overlaid by (mini)jet contribution
- This can also be looked at in two dimensions
  - Azimuth $\Delta\varphi$ and pseudorapidity $\Delta\eta$

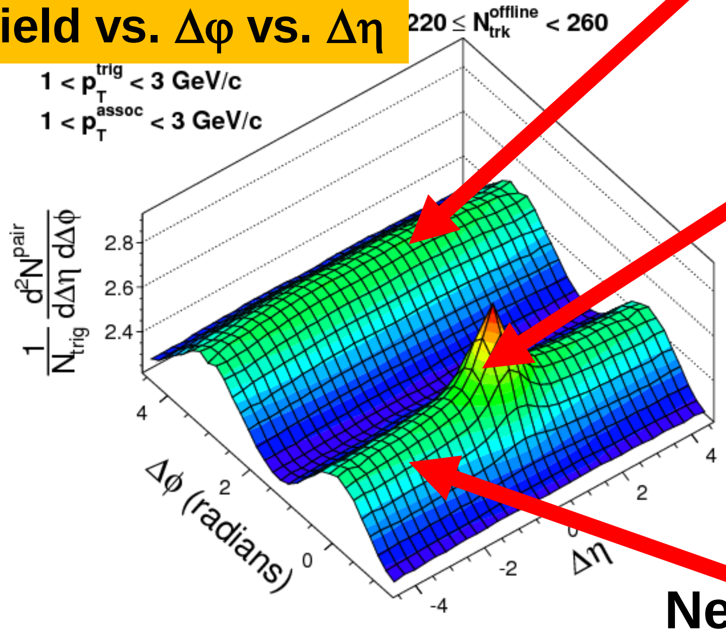


flow modulation

+ (mini)jet

include $\Delta\eta$ axis

Yield vs. $\Delta\varphi$ vs. $\Delta\eta$

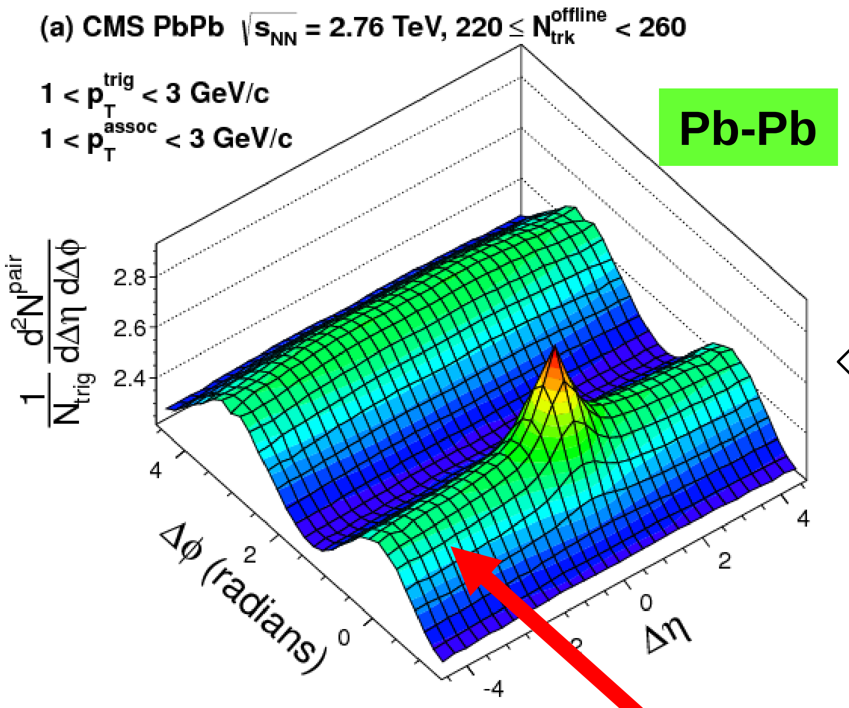


Away-side jet + flow ($\Delta\varphi \sim \pi$, elongated in $\Delta\eta$)

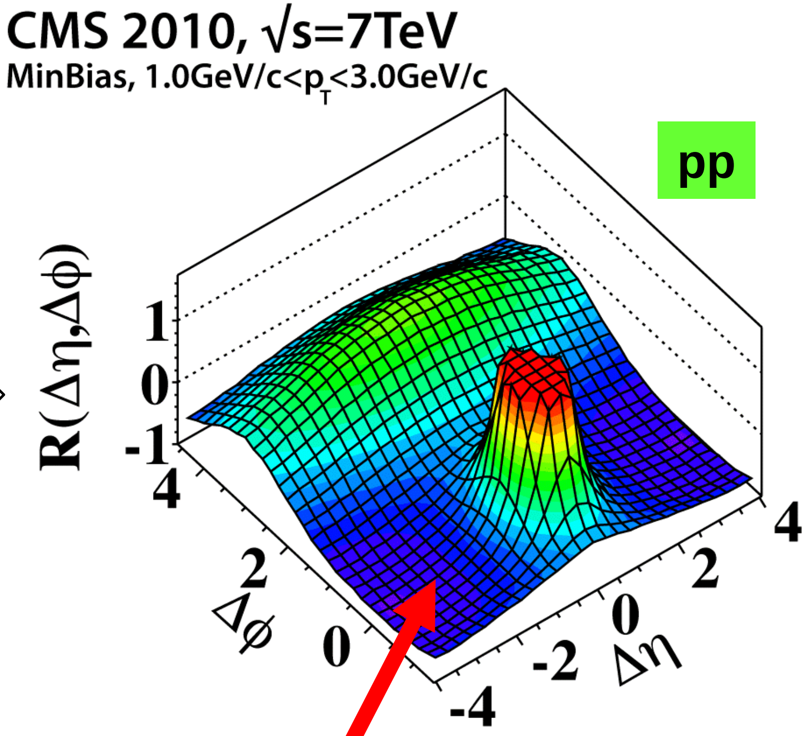
Near-side jet + resonances, ... ($\Delta\varphi \sim 0$, $\Delta\eta \sim 0$)

Near-side flow ridge ($\Delta\varphi \sim 0$, elongated in $\Delta\eta$)

And in pp?



Pb-Pb



pp

Near-side ridge (flow) only in Pb-Pb

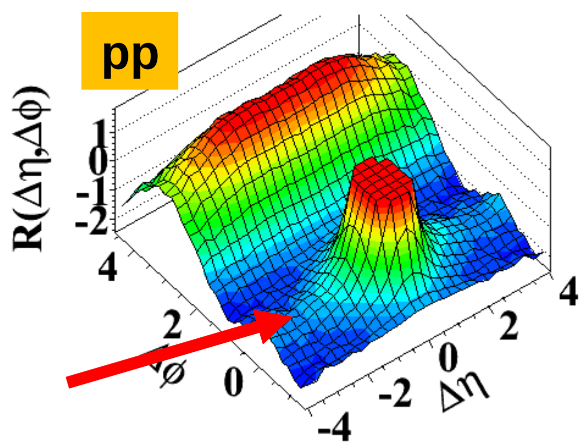
at least everyone thought so for a long time…

here: $\eta = \eta_{lab}$

Near-Side Ridge

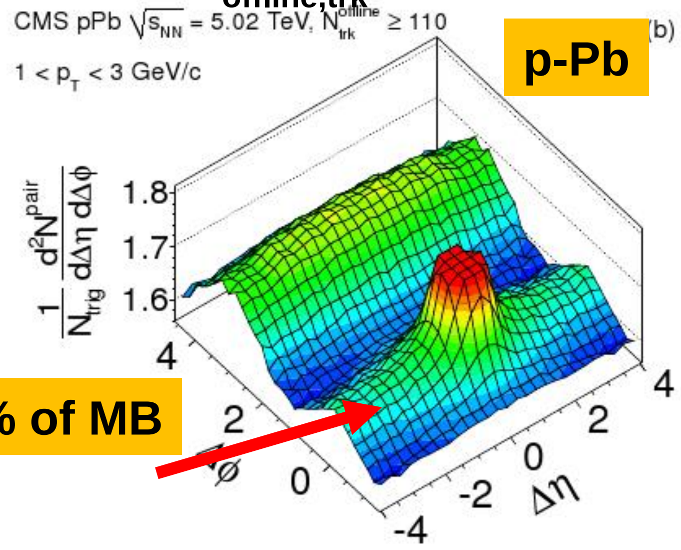
- …observed in very high-multiplicity pp collisions
  - 0.005% events with highest multiplicity
- …observed in high multiplicity p-Pb collisions
  - ~40% events with highest multiplicity
  - Surprisingly large magnitude

0.005% of MB



CMS, JHEP09(2010)091

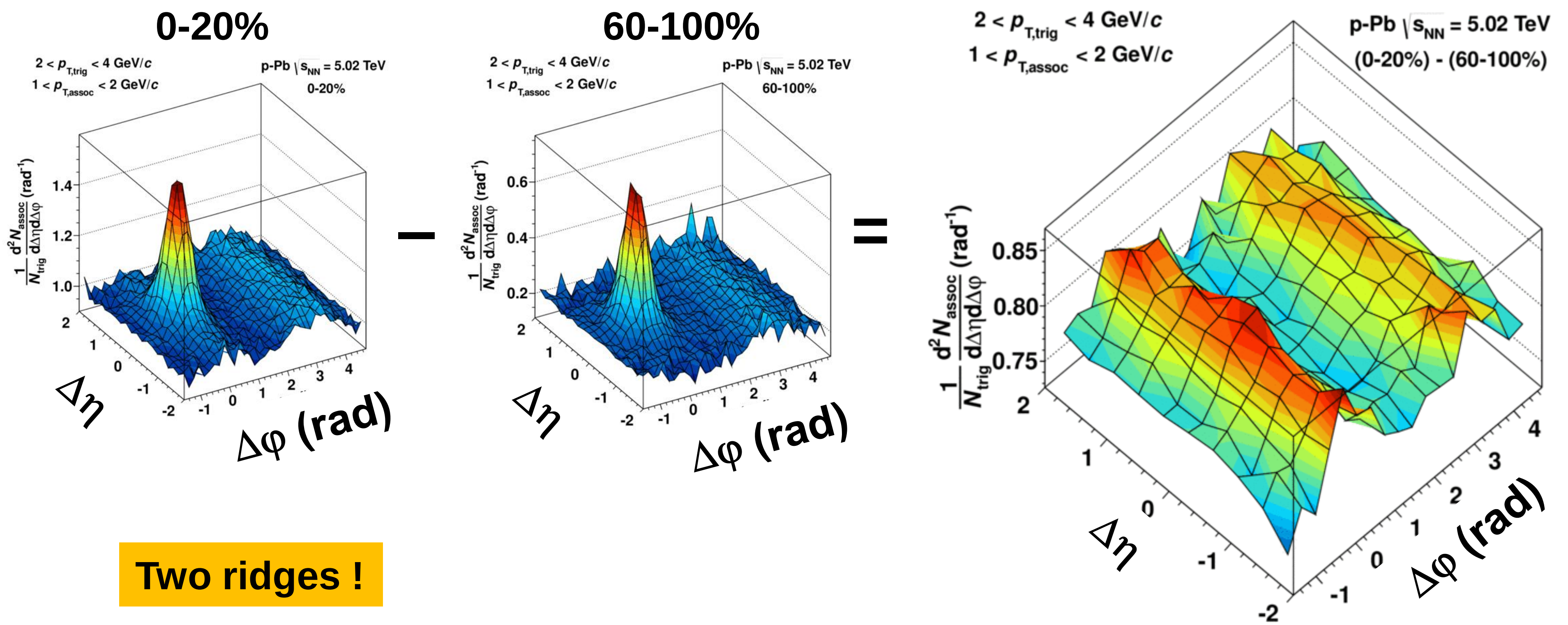
$N_{offline,trk} > 110$



CMS, PLB718 (2013) 795

Double Ridge in p-Pb

- Subtraction procedure to “isolate” ridge contribution from jet correlations
  - No ridge seen in 60-100% and similar to pp

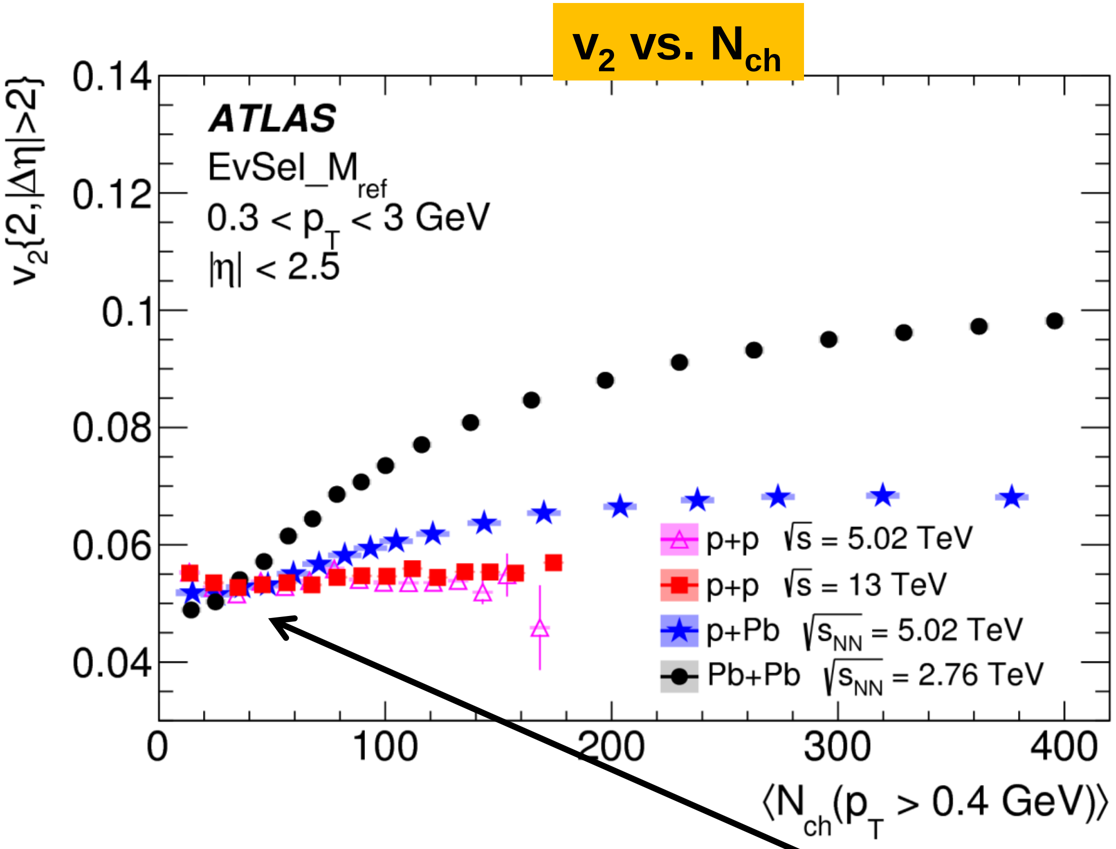


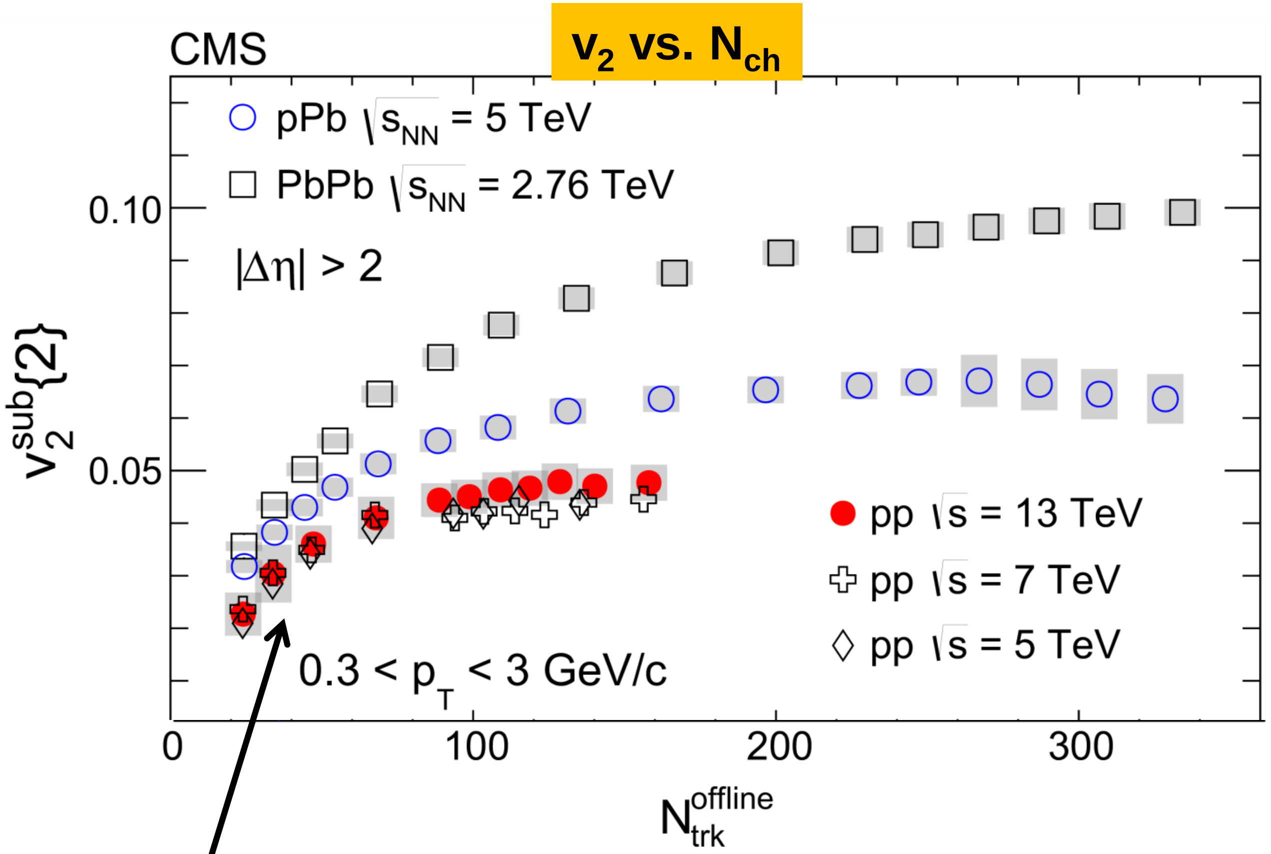
Two ridges !

ALICE, PLB719 (2013) 29

here: $\eta = \eta_{lab}$

v_2 Coefficients in pp



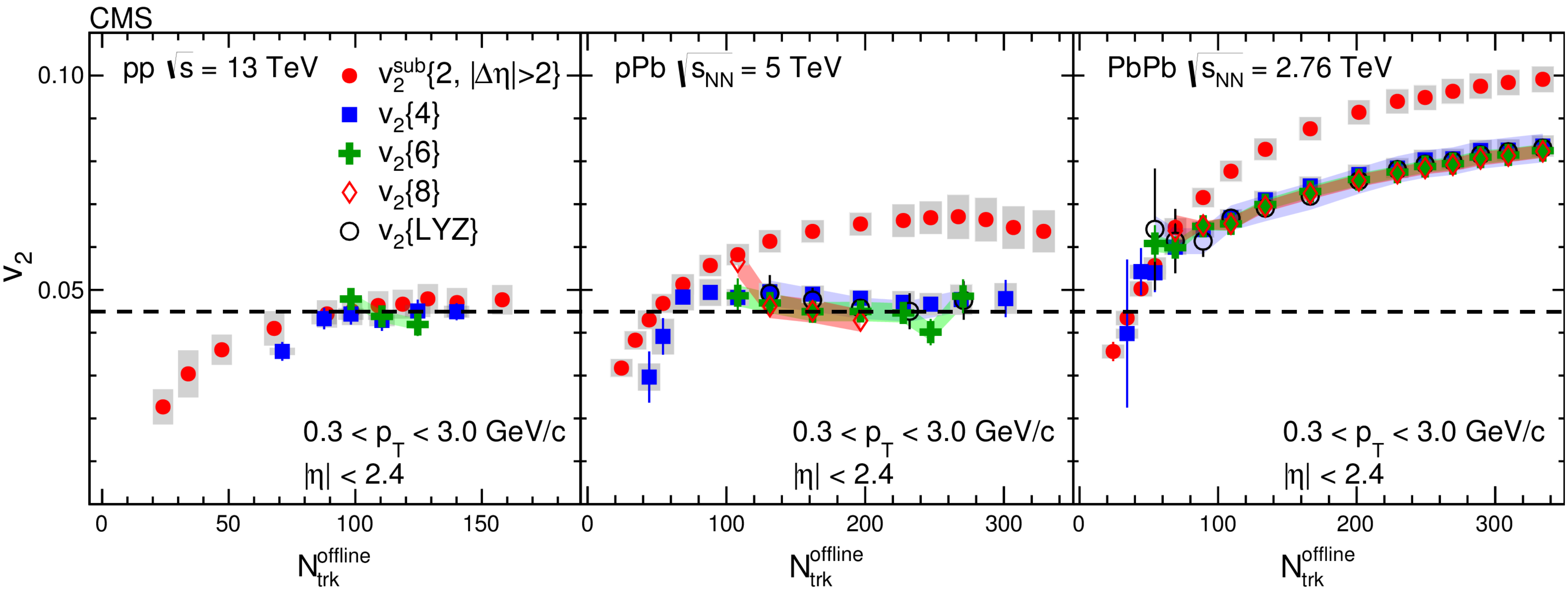


Low N_{ch} behaviour depends on procedure

Eur. Phys. J. C 77 (2017) 428

Phys. Lett. B 765 (2017) 193

System Comparison



Phys. Lett. B 765 (2017) 193

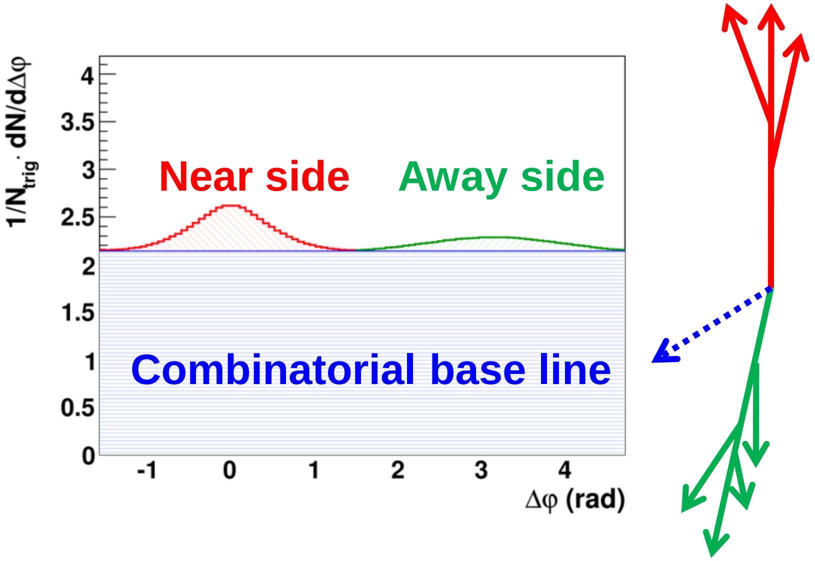
Recap

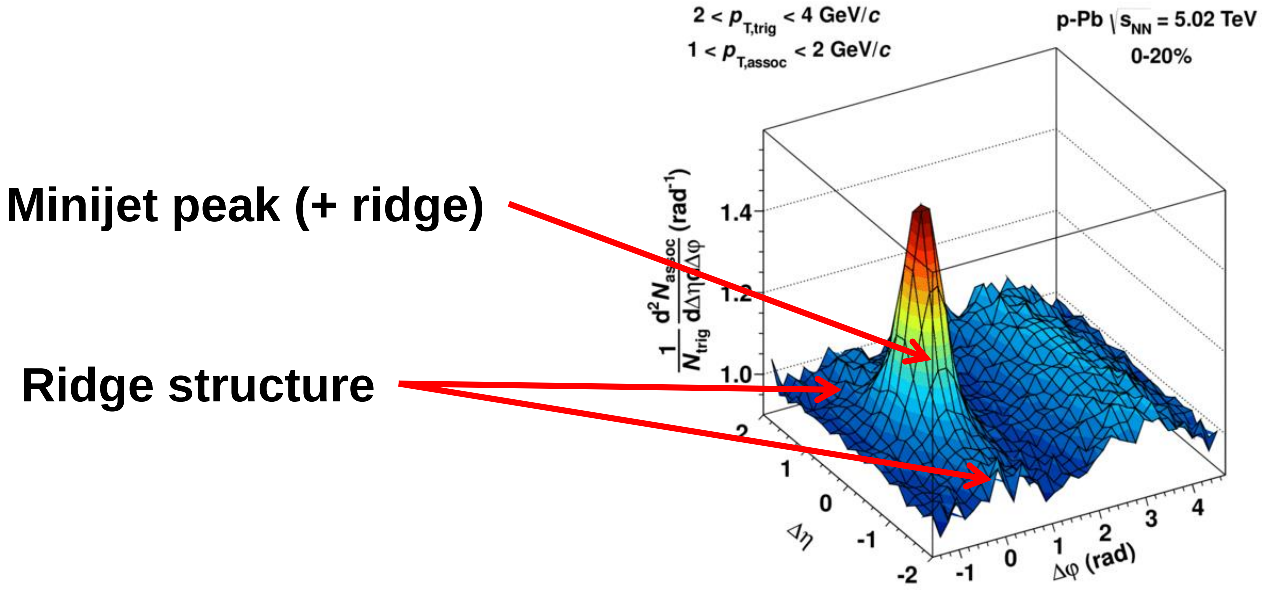
- In Pb-Pb collisions, correlations between all particles through a common symmetry plans are observed
- Small systems, p-Pb and (high-multiplicity) pp, show similar features
  - Paradigm shift in the understanding of heavy-ion collisions

- Can part of these effects be related to MPI and the correlations between them?
  - For this it is useful to answer the question if the observed ridge is related to the (mini)jet production

Uncorrelated Seeds in p-Pb

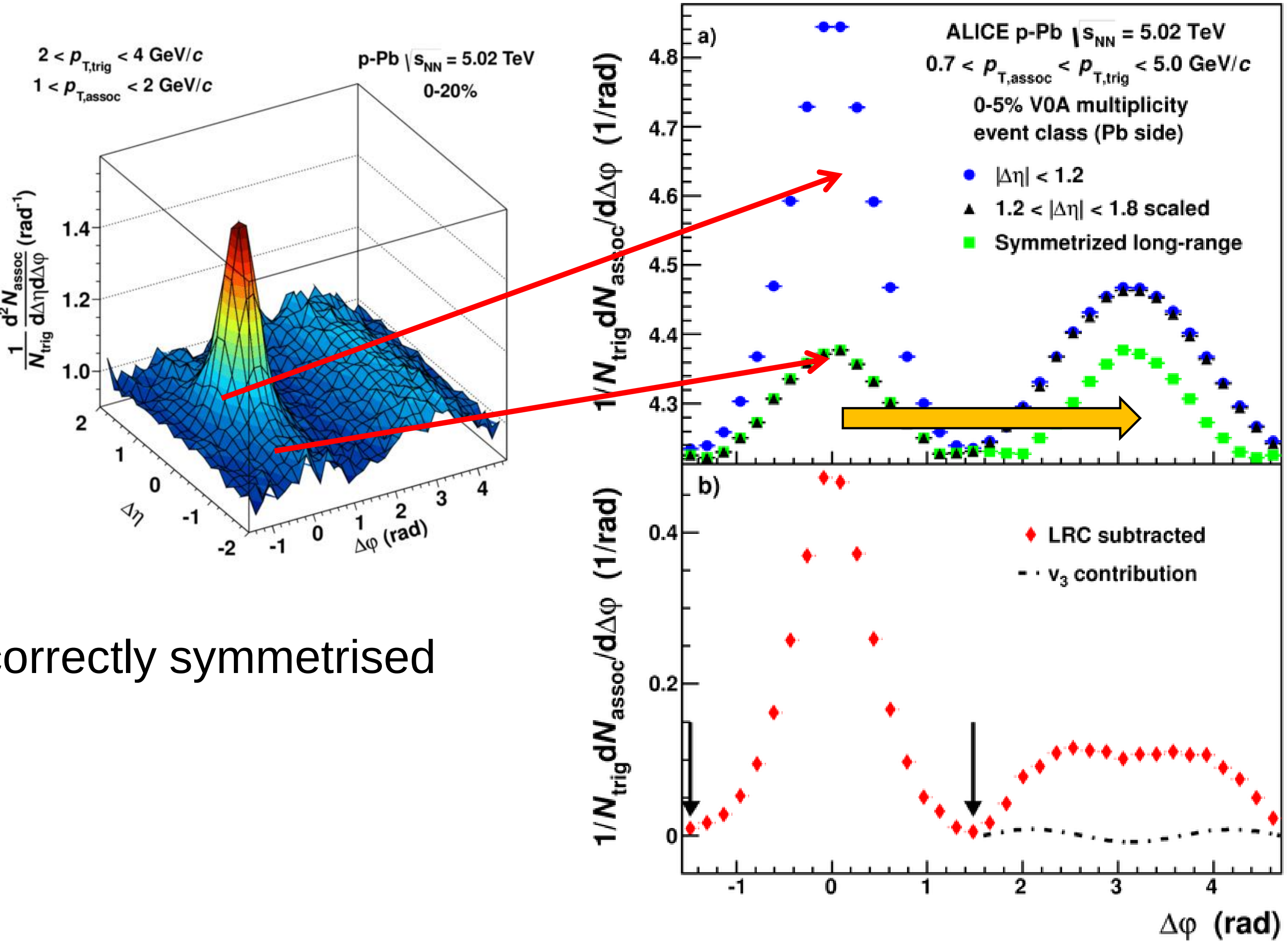
- Already discussed uncorrelated seeds measurement can be applied to p-Pb
  – Challenge: how to count particles in ridge?
  – Exploit two-dimensional (Δφ and Δη) near-side structure





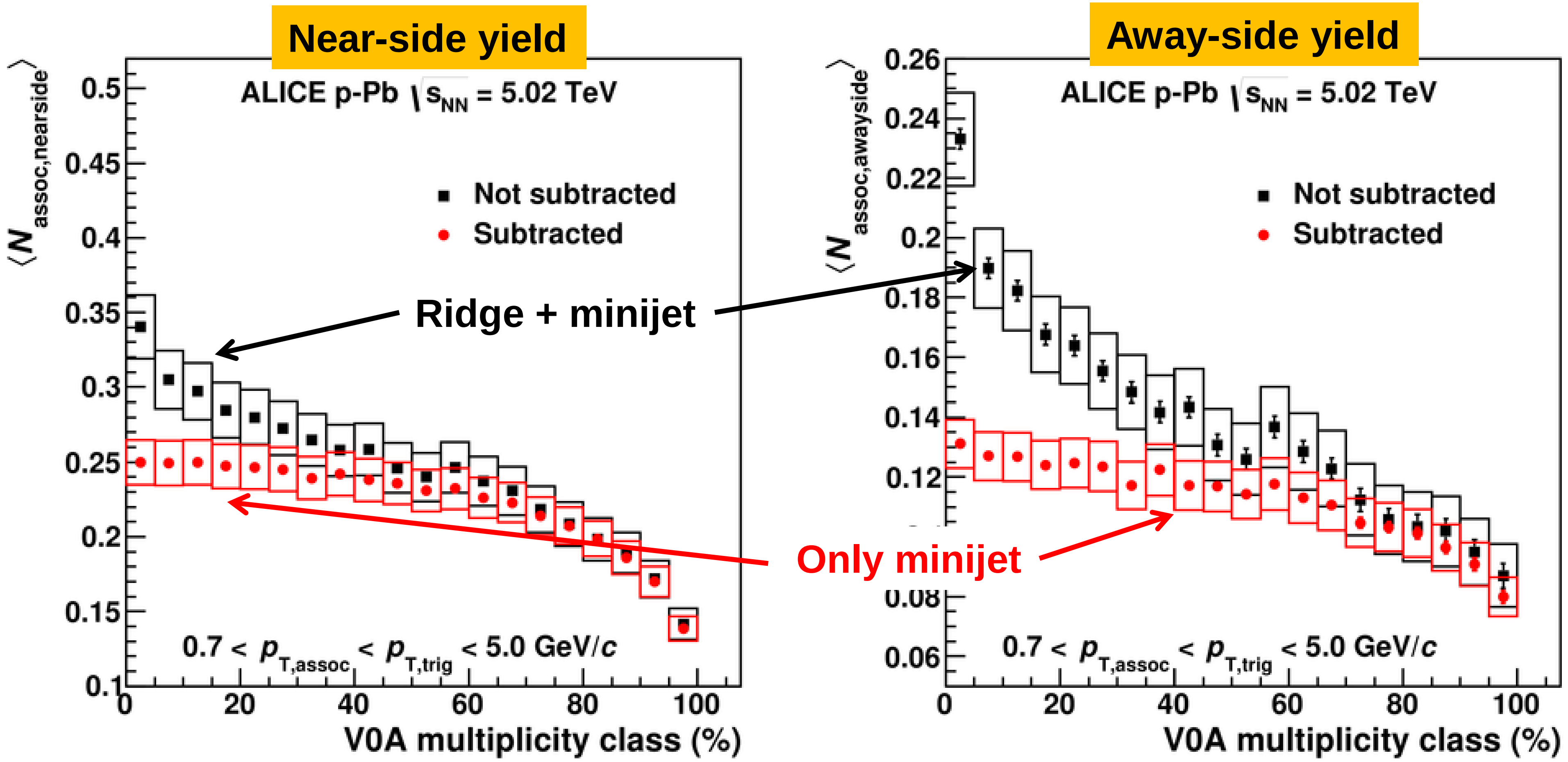
Ridge Subtraction

- Short range ($|\Delta\eta| < 1.2$)
- Long range ($|\Delta\eta| > 1.2$)
  - Symmetrise to away side
  - Subtract
- Caveats?
  - Odd harmonics (like v_3) not correctly symmetrised → systematic uncertainties



Phys. Lett. B 741 (2015) 38-50

Near-Side and Away-Side Yields



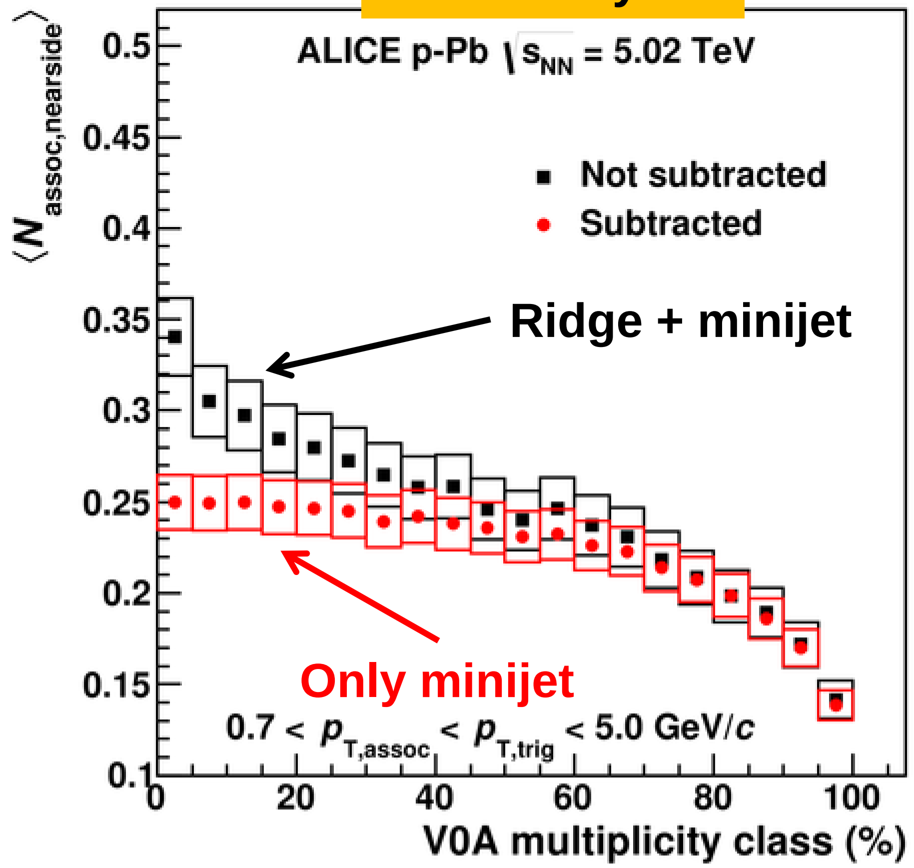
highest N_{ch} **lowest N_{ch}**

Phys. Lett. B 741 (2015) 38-50

Minijet contribution flattens for highest 60% multiplicity

Correlation of Hard and Soft

Near-side yield



- Observable = associated yield/trigger
- Associated yield = particles from minijet
- Trigger = particles from minijet + uncorrelated bg
- Simple scenario
  - $N_{minijets}$ with $N_{associated}$ particles each
  - Some soft background N_{soft}

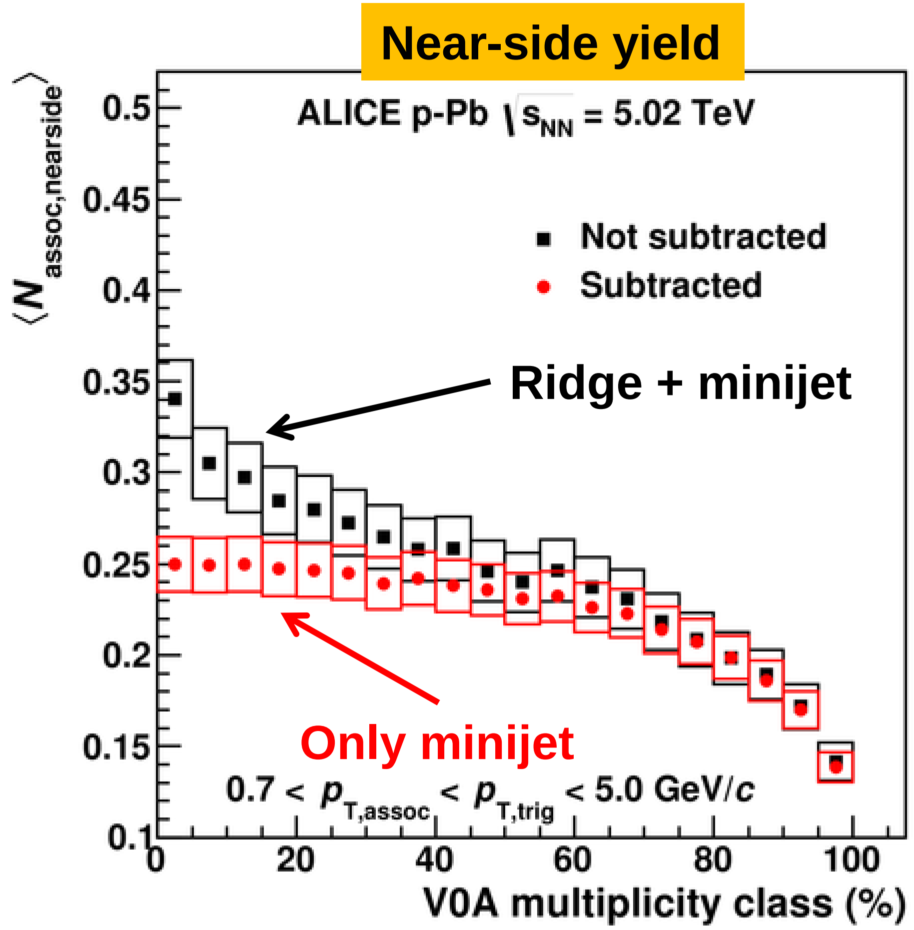
$$\frac{\text{associated yield}}{\text{trigger particle}} = \frac{N_{\text{minijets}} \cdot N_{\text{assoc}}(N_{\text{assoc}} - 1)/2}{N_{\text{minijets}} \cdot N_{\text{assoc}} + N_{\text{soft}}}$$

= overall mult. N_{ch}

- Quantity stays constant with N_{ch} only if $N_{minijets}$ and N_{soft} change by same factor → hard and soft particle production exhibit same evolution with multiplicity

Phys. Lett. B 741 (2015) 38-50

Correlation of Hard and Soft



$$\frac{\text{associated yield}}{\text{trigger particle}} = \frac{N_{\text{minijets}} \cdot N_{\text{assoc}}(N_{\text{assoc}}-1)/2}{N_{\text{minijets}} \cdot N_{\text{assoc}} + N_{\text{soft}}}$$ **= overall mult. N_{ch}**

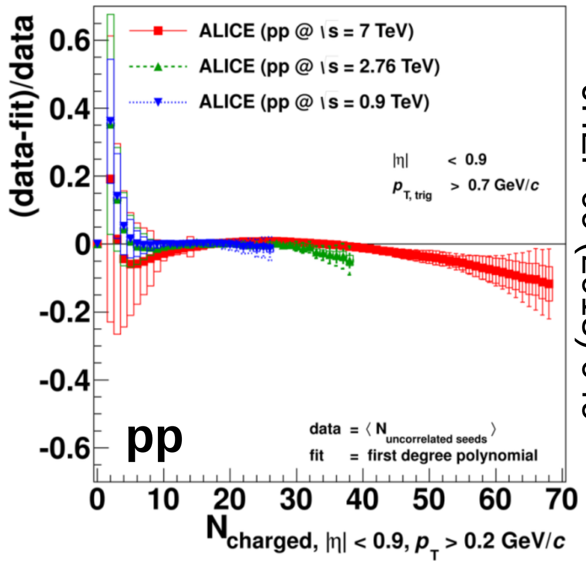
- Quantity stays constant with N_{ch} only if $N_{minijets}$ and N_{soft} change by same factor → hard and soft particle production exhibit same evolution with multiplicity
- Statement doesn't hold when ridge included

- Conclusion
  – Independent parton-parton scatterings + incoherent fragmentation produce minijets
  – Ridge is result of other source(s)

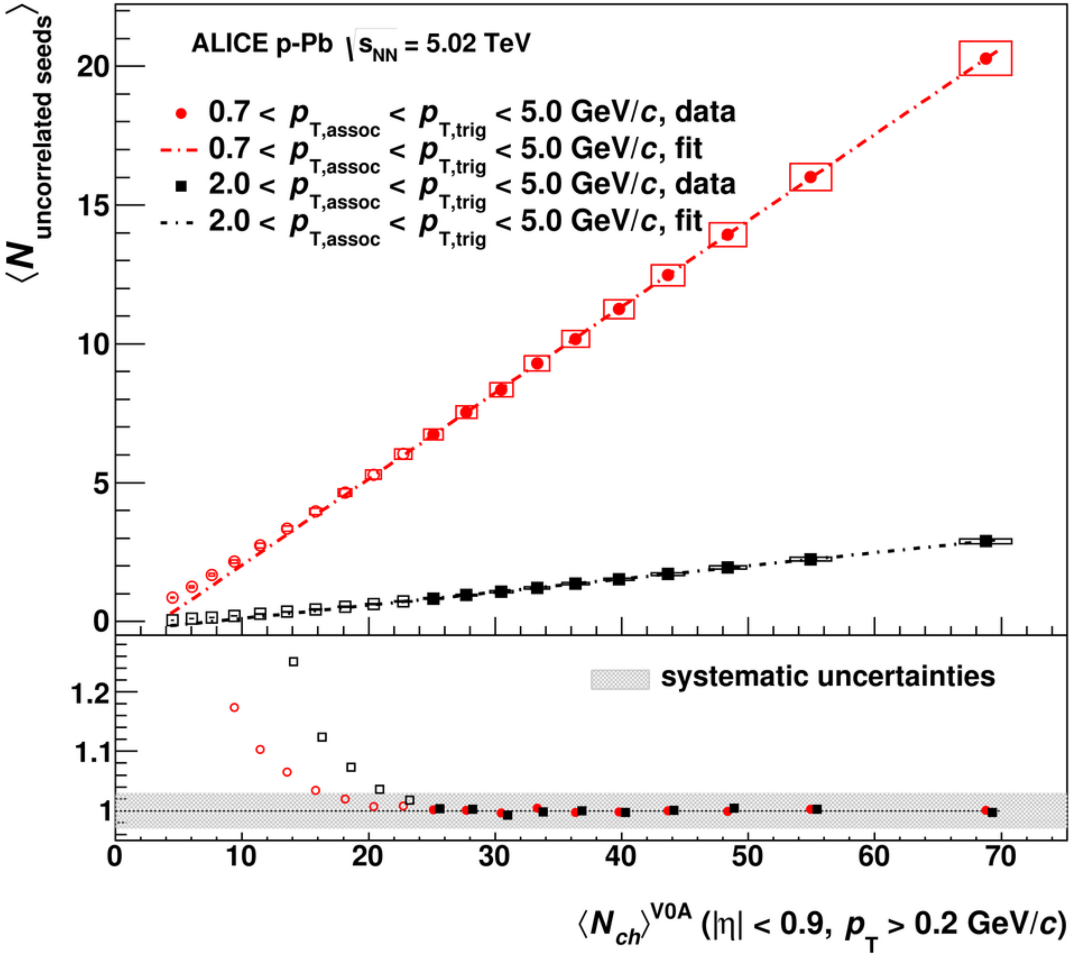
Phys. Lett. B 741 (2015) 38-50

Saturation of MPI in p-Pb?

- Uncorrelated seeds after subtraction of ridge component
- Linear growths with multiplicity
- No sign of saturation of number of MPI as hinted at in pp collisions



JHEP 09 (2013) 049



Phys. Lett. B 741 (2015) 38-50

Summary
Collective Phenomena

- Expanding hot and dense matter leads to collective phenomena
  - All particles correlated with each other through common symmetry planes
  - Text-book observable in heavy-ion collisions
- Similar effects observed in small collision systems
  - Involving ions on one side: (p-A, d-A)
  - In pp collisions well established at high N_{ch}; under investigation at low N_{ch}
- Ridge structure in p-Pb collisions seems to be additive to minijets produced by independent parton-parton scatterings + incoherent fragmentation

Take-Home Messages

- Multiplicity distribution of events with different number of PI very different, but experimentally inaccessible
- Underlying event transverse region measures activity from additional PI in the same collision
- Uncorrelated seeds extracted from two-particle correlations are proportional to the number of PI (in MCs)
- Hard probes like D and J/ψ measured as a function of multiplicity are a proxy of the correlation of the production of hard and soft probes
- Double parton scattering quantifies with σ_{eff} the probability that two hard processes occur in the one collision in different parton scatterings
- Multiplicity as event characterization suffers from various biases which have to be considering before drawing physics conclusions
- The collective ridge structure observed in small systems is additive to minijets produced by MPI

Thank you for your attention!

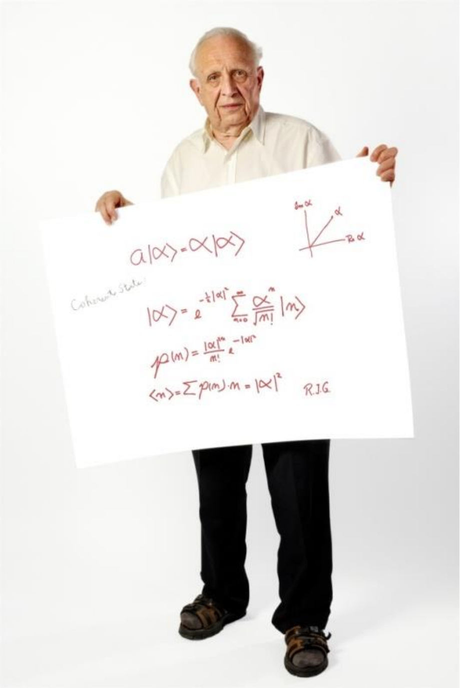
Backup

Toy for Selection Bias

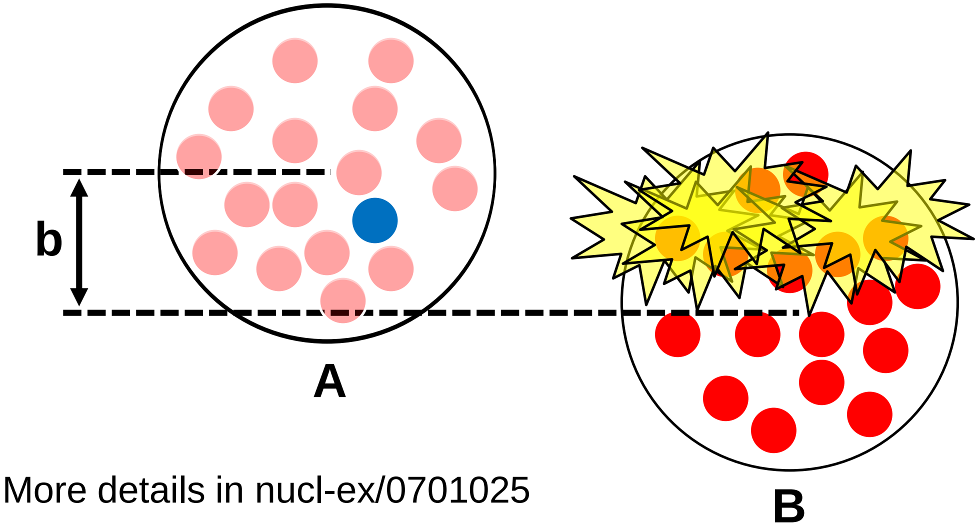
```
#include "TF1.h"
#include "TMath.h"
#include "TProfile.h"
#include "TCanvas.h"
#include "TH2F.h“

void selection_bias() {
  TF1* ptDist = new TF1("ptDist",
    "x**-4.4", 0.5, 10);
  TProfile* prof = new TProfile("prof",
    ";p_{T,lead};N_{ch}", 100, 0, 10);

  for (int trial=0; trial<10000; trial++) {
    for (int n=1; n<50; n++) {
      double maxpt = 0;
      for (int i=0; i<n; i++)
        maxpt = TMath::Max(maxpt,
    ptDist->GetRandom());
      prof->Fill(maxpt, n);
    }
  }

  new TCanvas;
  prof->SetStats(kFALSE);
  prof->Draw("COLZ");
}
```

Glauber Monte Carlo

- Nucleons travel on straight lines
- Collisions do not alter their trajectory (energy of nucleons large enough)
- No quantum-mechanical interference
- Interaction probability for two nucleons is nucleon-nucleon cross-section



Roy Glauber



“Blue” nucleon has suffered 5 NN collisions

Need to repeat for all other nucleons in A

Strongly dependent on *impact parameter* b

More details in nucl-ex/0701025

Realistic Example

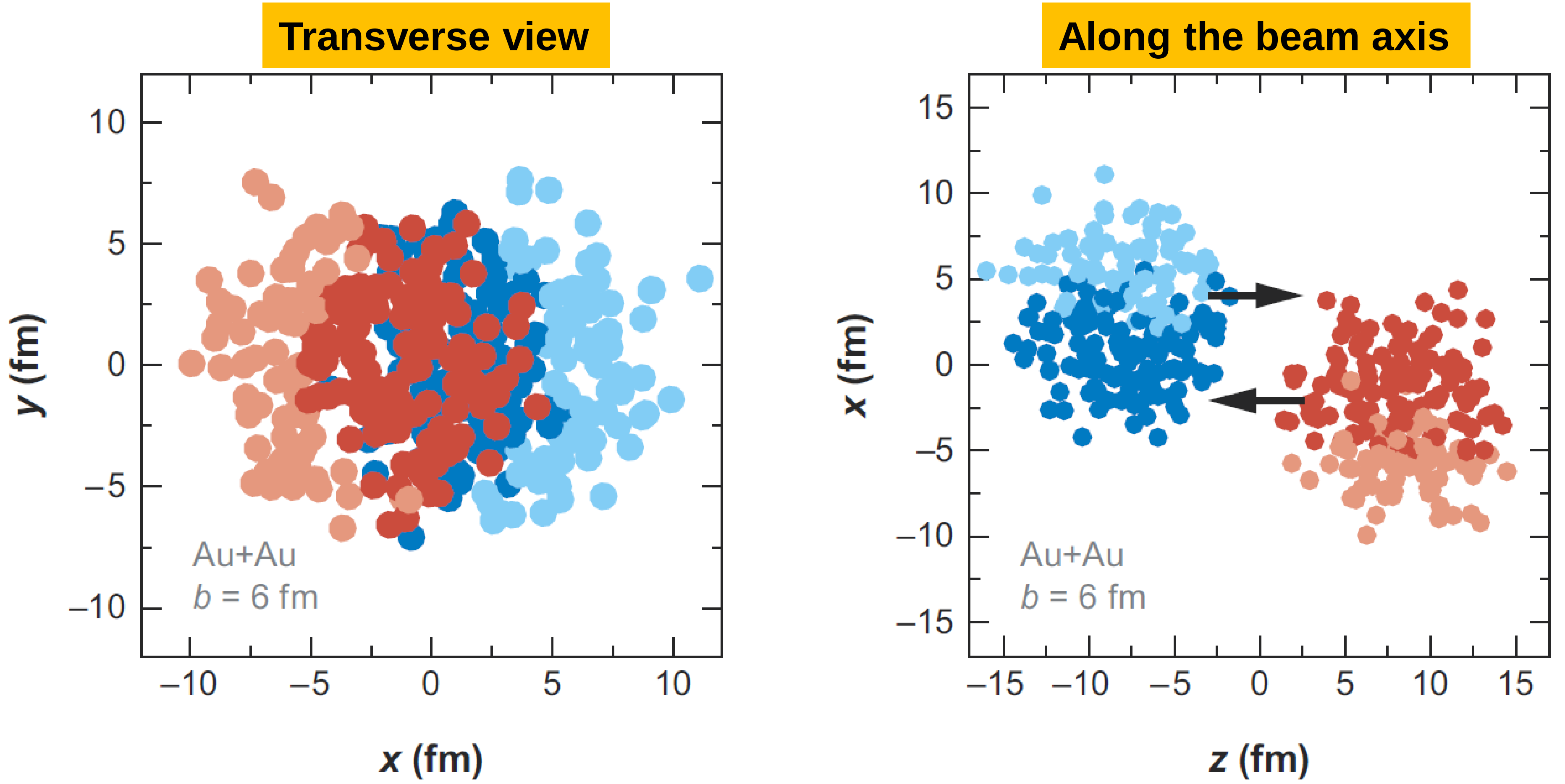


Figure: nucl-ex/0701025

Input to Glauber MC

- Distribution of nucleons in nuclei
  - Based on nuclear density
  - Typically Woods-Saxon distribution

$$\rho(r) = \rho_0 \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}$$

Nuclear radius R

Skin depth a

Density in the center

- Nucleon-nucleon cross-section
  - From pp measurements / extrapolations

ρ(r)/ρ(0) vs. r

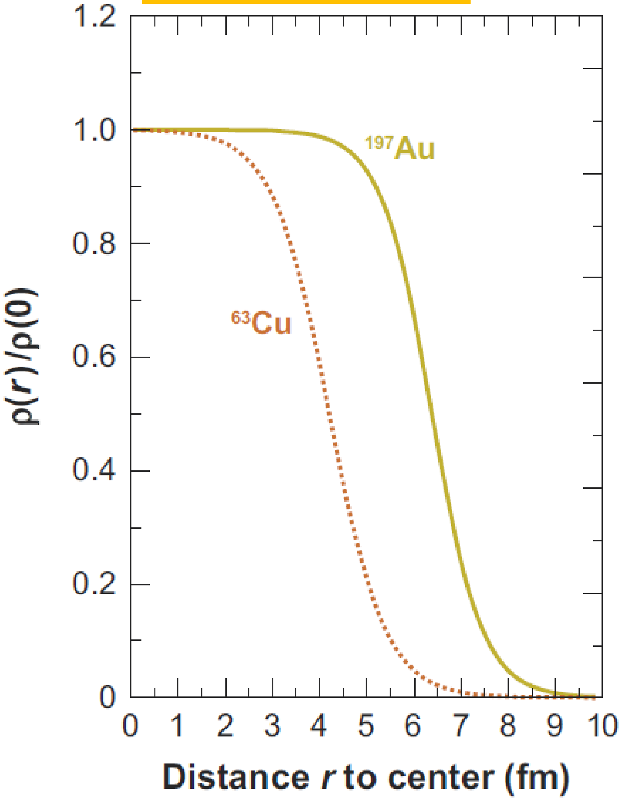
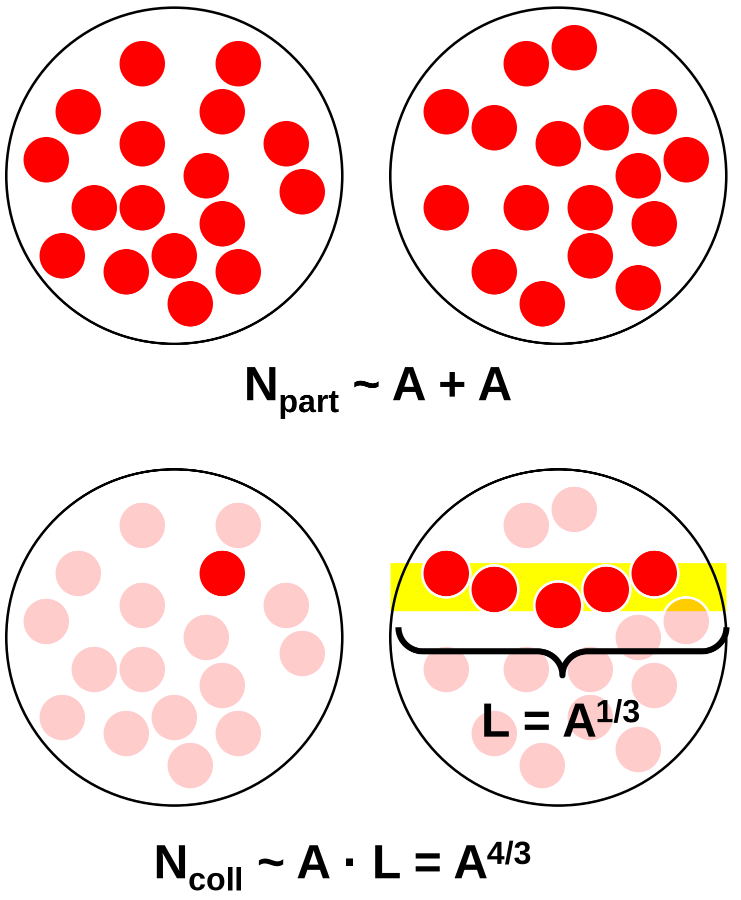


Figure: nucl-ex/0701025

Glauber MC Output

- Number of spectators
  - Nucleons which did not collide
- Participant/wounded nucleons
  - Collided at least once
  - Called N_{part}
  - Scale with 2A (A = number of nucleons)
- Number of binary collisions
  - Called N_{coll}
  - Scales with $A^{4/3}$
- Rule of thumb
  - Soft (low p_T) observables scale with N_{part}
  - Hard (high p_T) observables scale with N_{coll}



Glauber MC Output (2)

- 10% most central at RHIC (Au-Au, 200 GeV)
  - N_{coll} ~ 1200
  - N_{part} ~ 380
- 5% most central collisions at LHC (Pb-Pb, 5 TeV)
  - N_{coll} ~ 1770
  - N_{part} ~ 384
- Difference mainly due to cross-section increase

N_{coll}, N_{part} vs. b