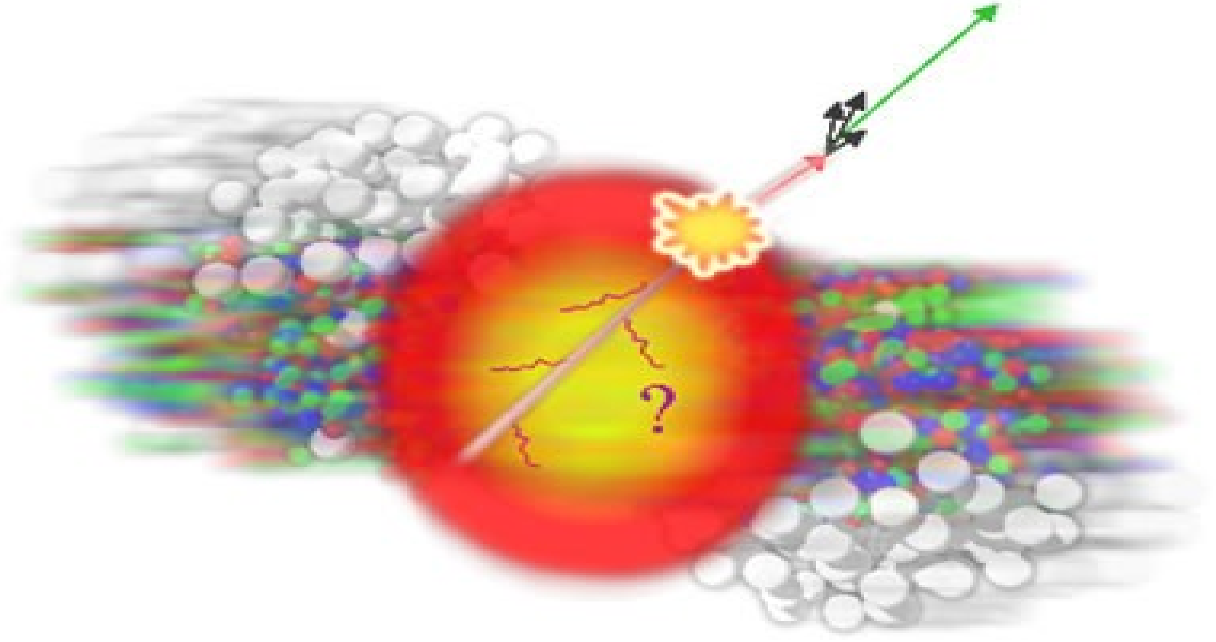
A skeptic's guide to jets
Part 1: Jet spectra



Christine Nattrass
University of Tennessee, Knoxville

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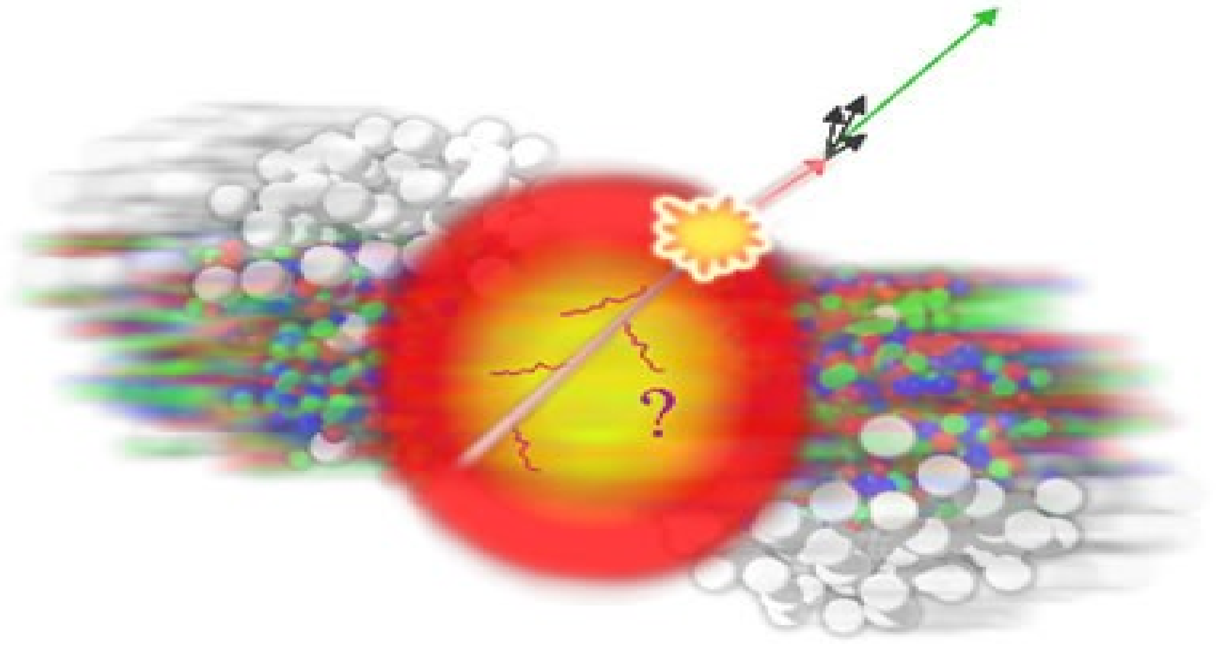
Part 1: Jet spectra



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Abhijit Majumder, Raghav Kunnawalkam Elayavalli
Marta Verweij, Laura Havener
Austin Schmier, Charles Hughes, Will Witt

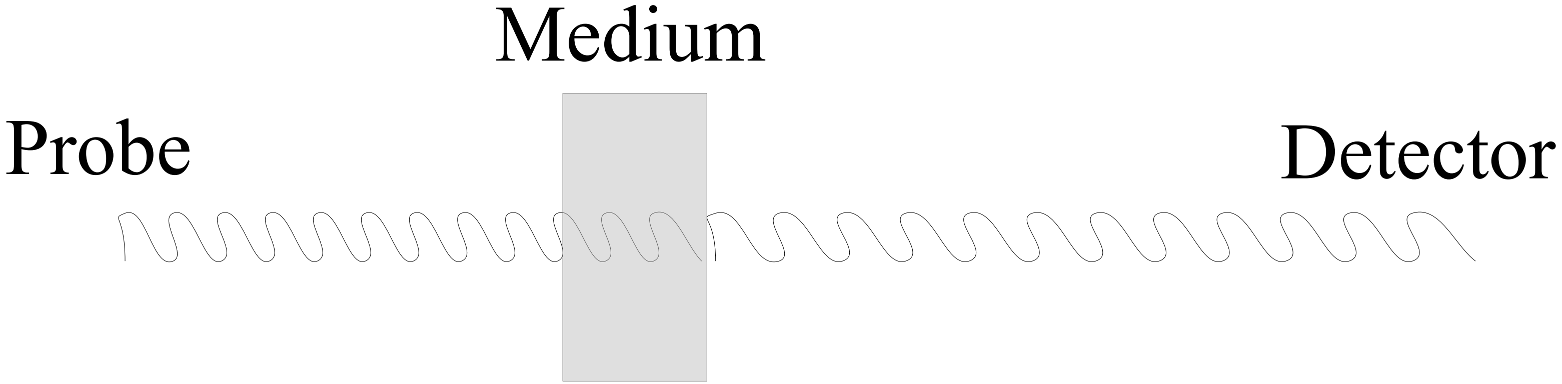
Questions an experimentalist should ask

- What do I want to learn?
- What am I measuring?
- What assumptions am I making?
- What are the dominant uncertainties?
- How do I compare to models?

The answers for jets are highly non-trivial!

What do I want to learn?
The cartoon picture

Probing the Quark Gluon Plasma

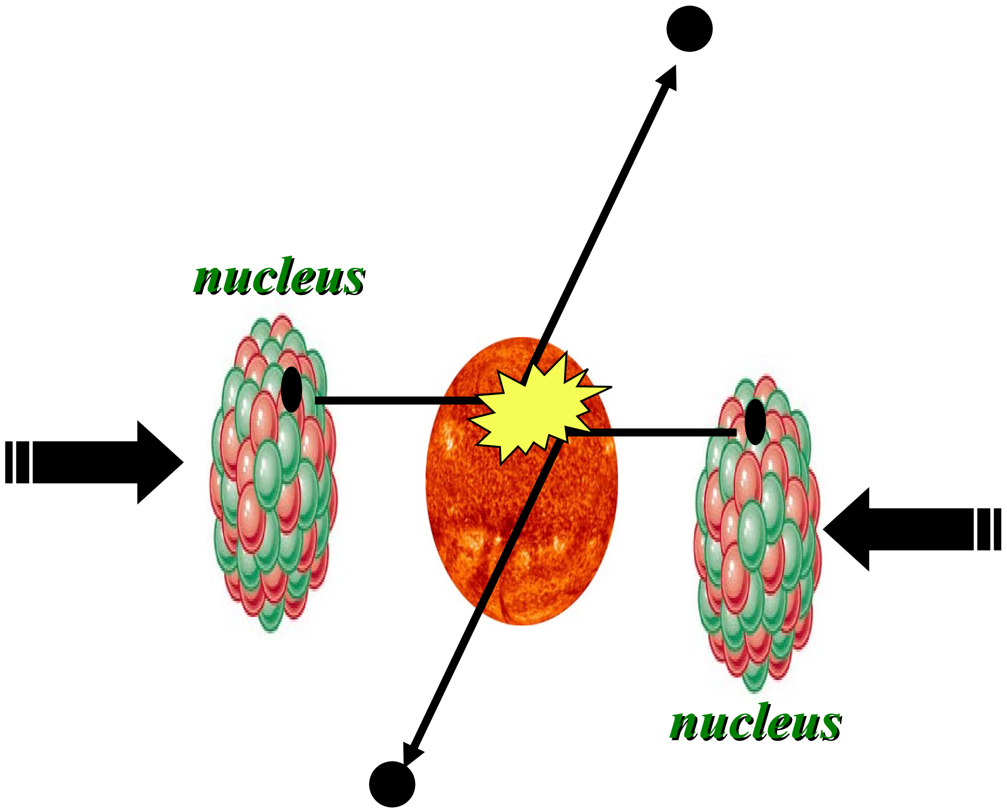


Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium

QGP is short lived → need a probe created in the collision

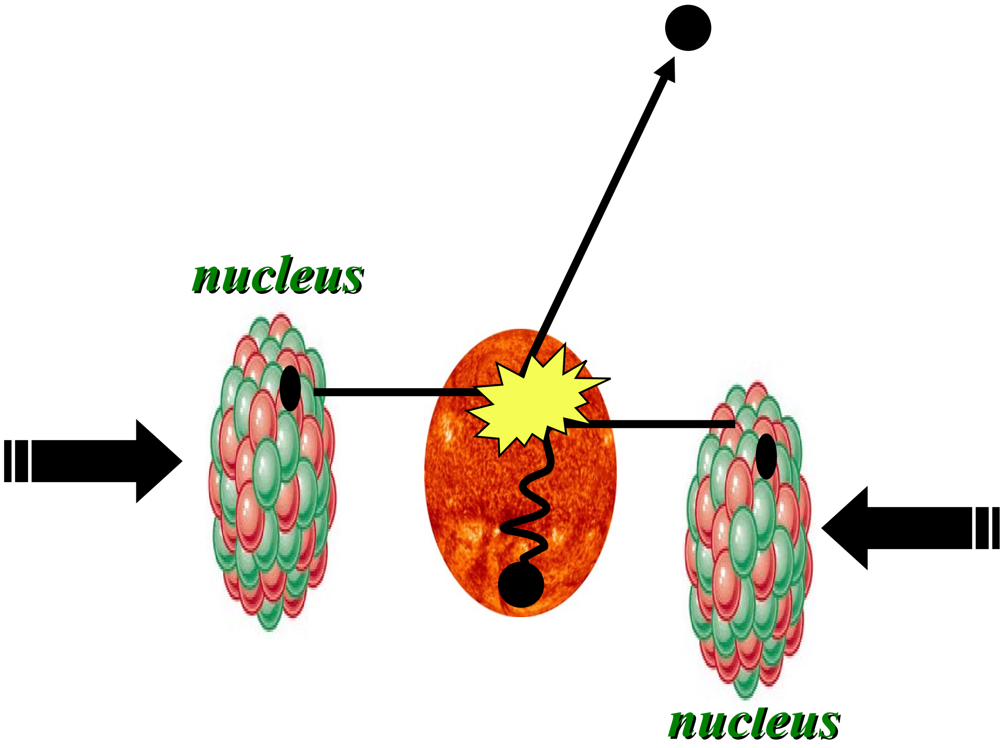


Probes of the Quark Gluon Plasma

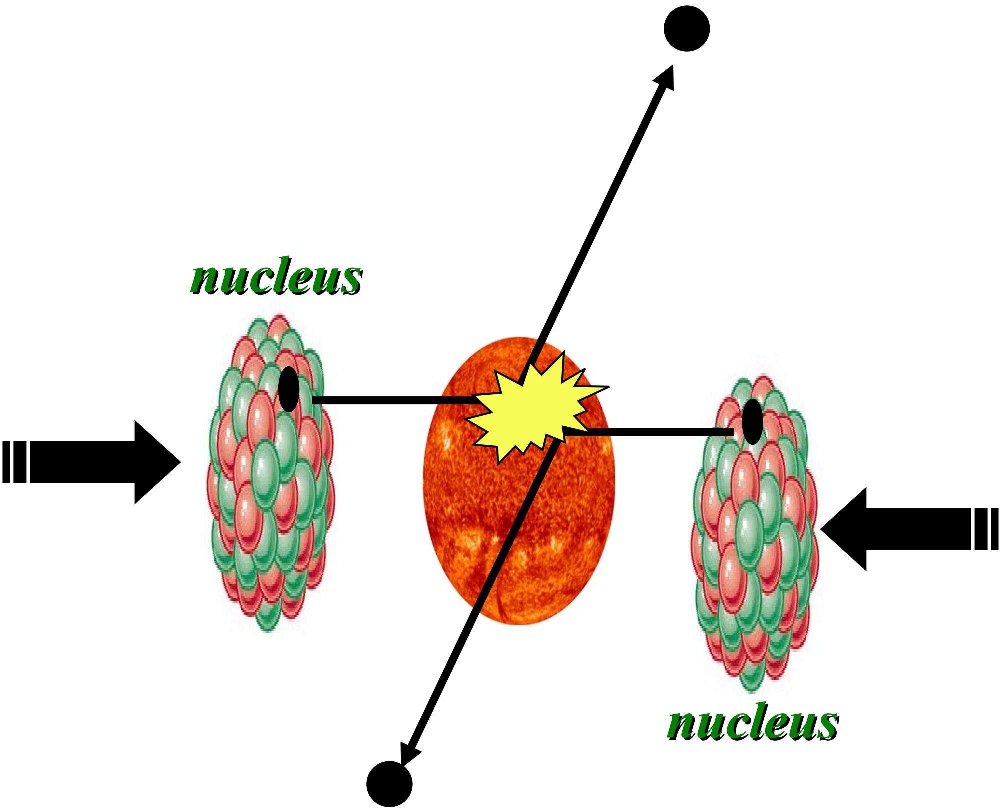
Want a probe which traveled through the medium

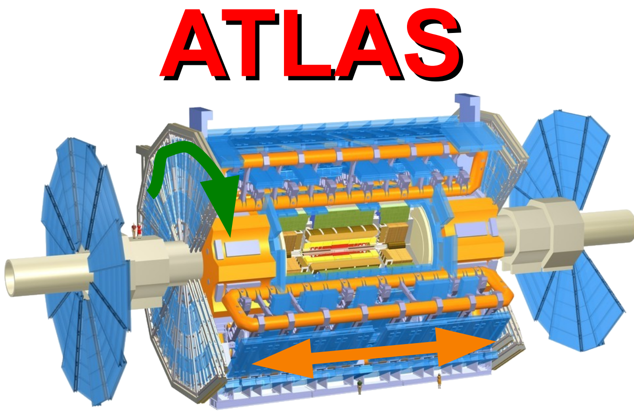
QGP is short lived → need a probe created in the collision

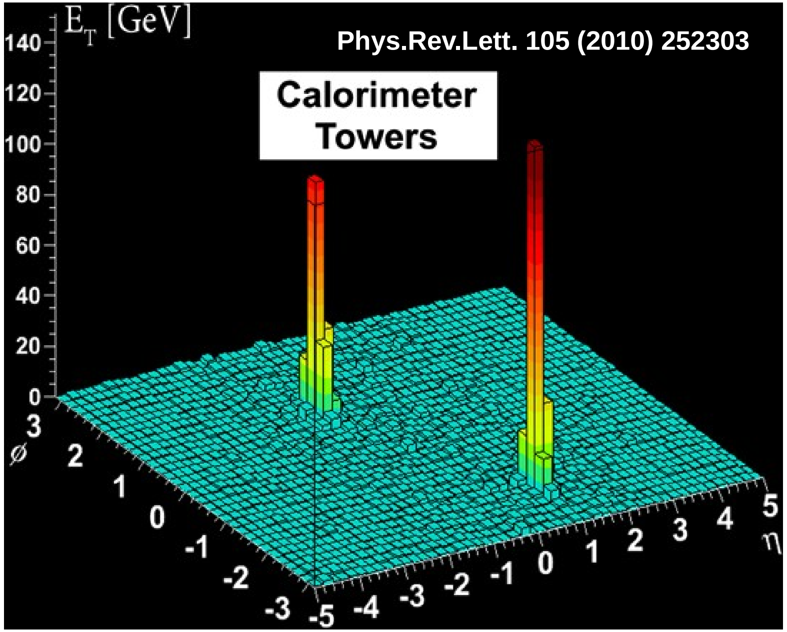
We expect the medium to be dense → absorb/modify probe



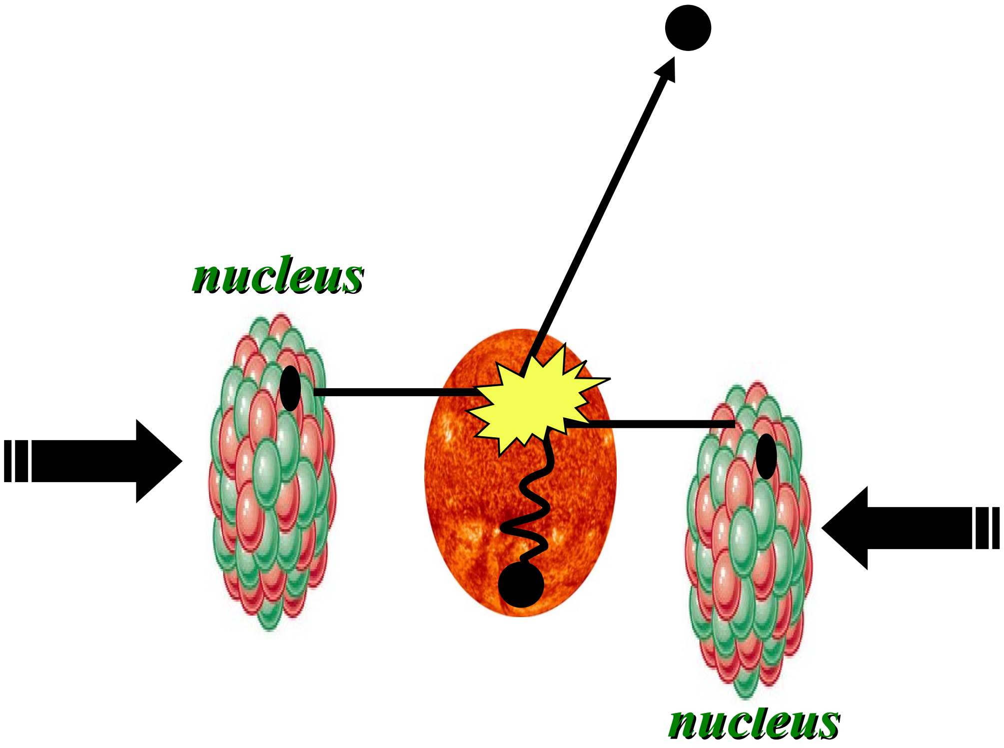
Probes of the Quark Gluon Plasma

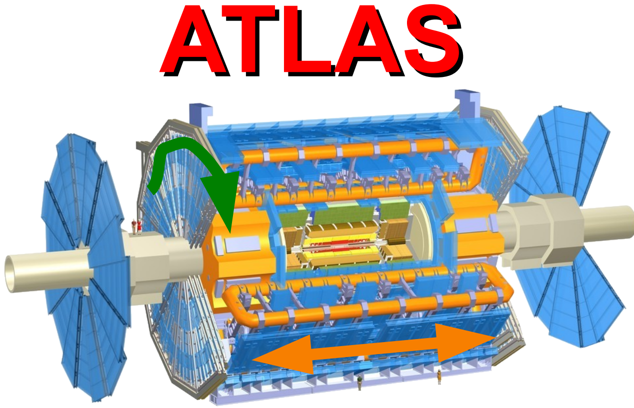


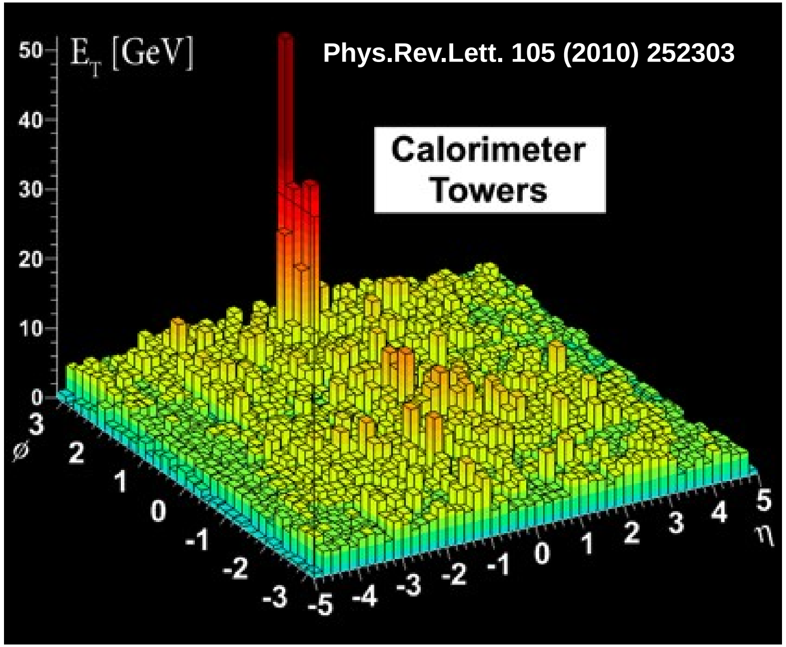




Probes of the Quark Gluon Plasma





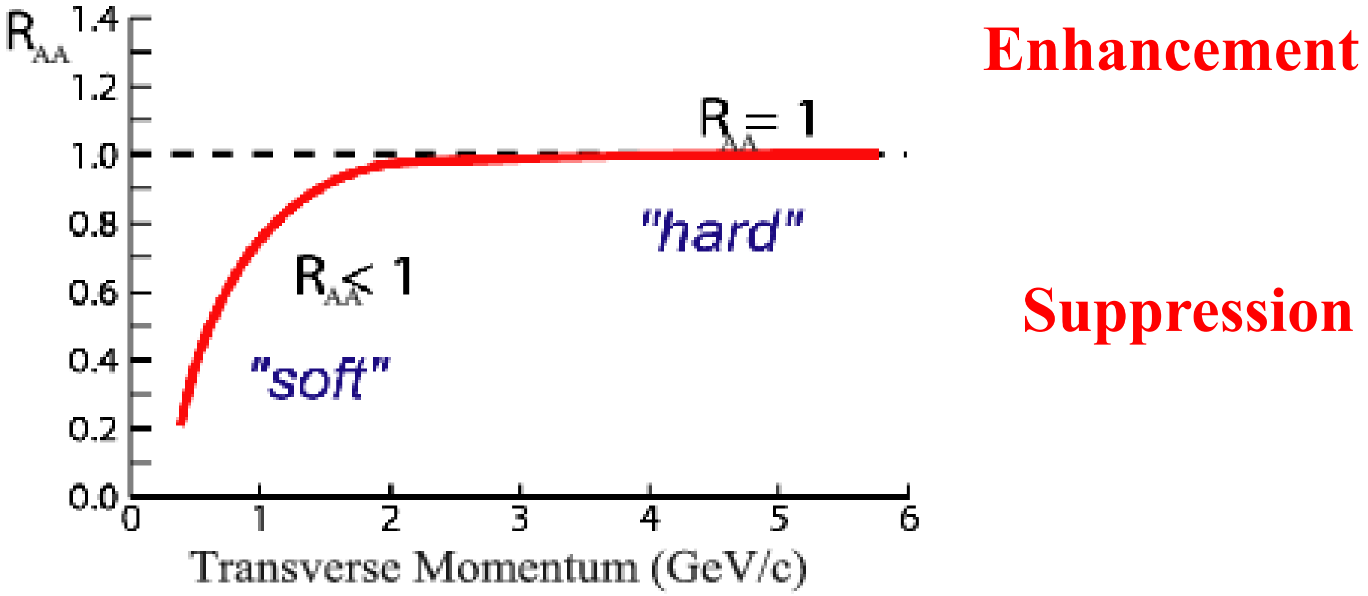


“Simple” example: Single hadrons

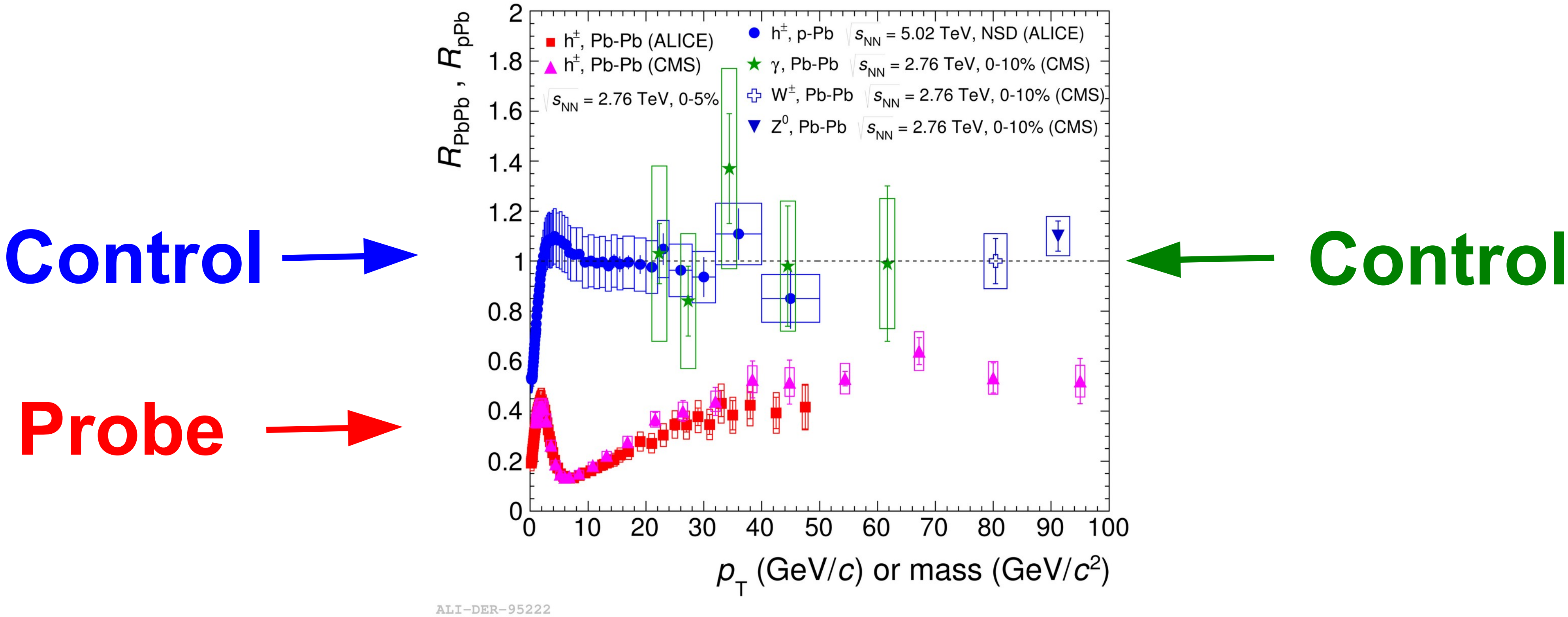
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$

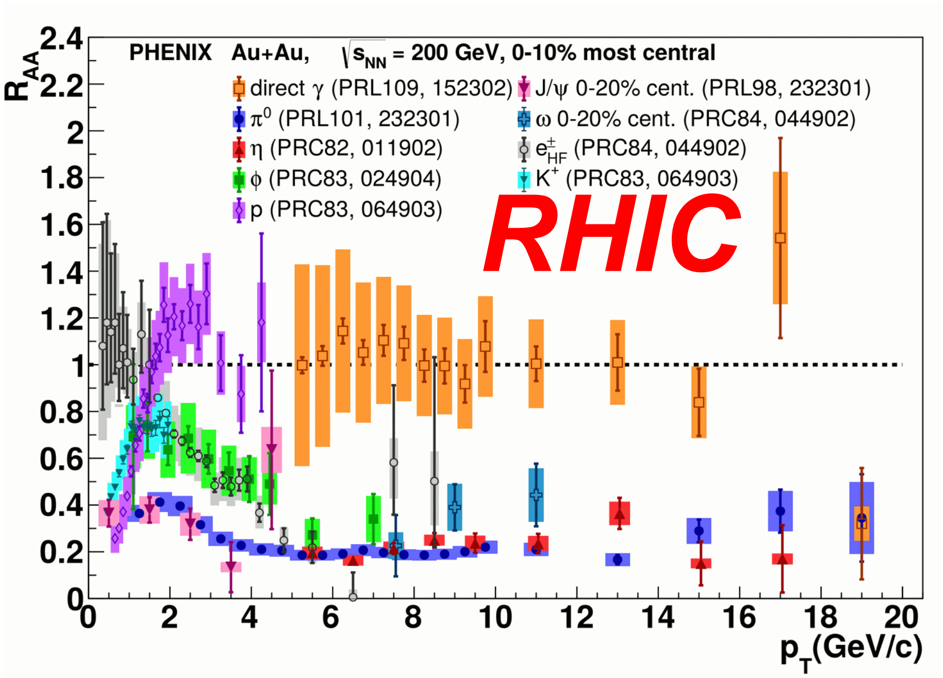


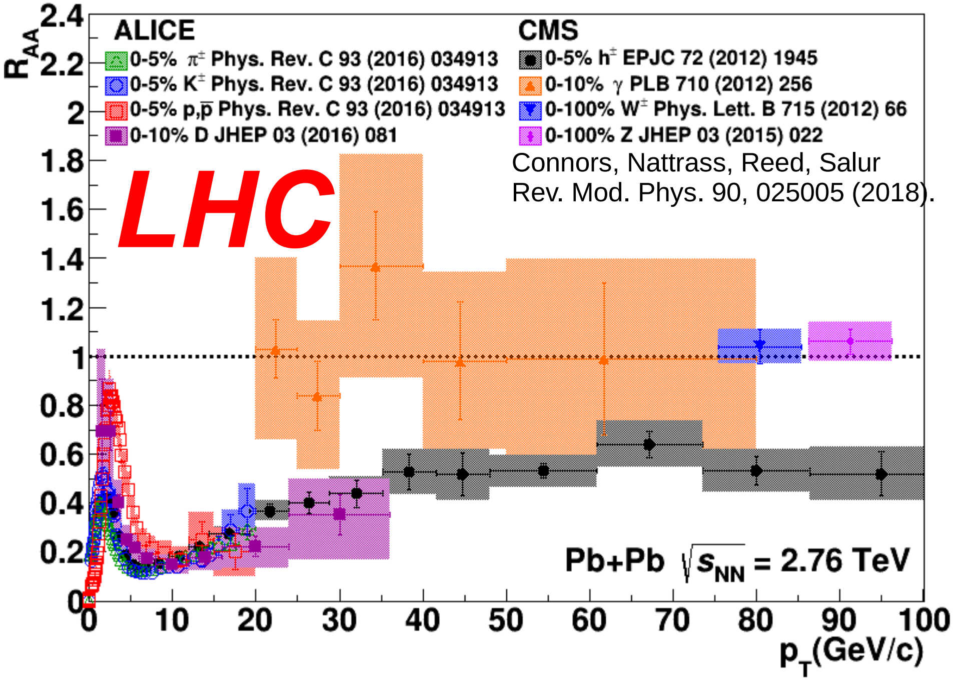
Nuclear modification factor



- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}





Electromagnetic probes – consistent with no modification – medium is transparent to them

Strong probes – significant suppression – medium is opaque to them - even heavy quarks!

What am I measuring?
Definition of a jet

Theoretical calculations

Factorization theorem

- Assumption: Parton distribution functions, perturbative cross section, fragmentation function factorize
- What people really mean by "perturbatively calculable"
  - *D and f are explicitly non-perturbative!*
  - D is for *parton c → hadron h* *Not* what is experimentally measured
- Most theories for jet quenching modify fragmentation function D

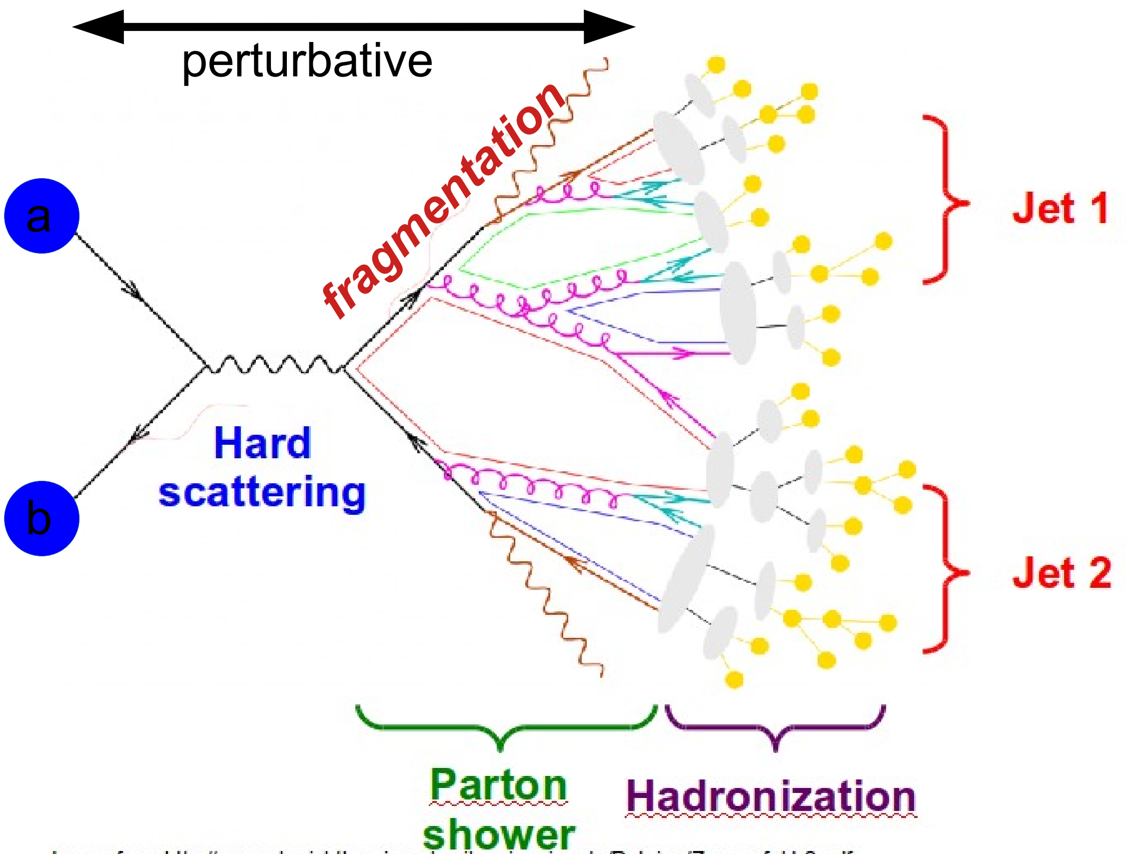


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

$$\frac{d^3\sigma^h}{dy\, d^2 p_T} = \frac{1}{\pi}\int d\,x_a \int d\,x_b f_a^A(x_a) f_b^B(x_b) \frac{d\,\sigma_{ab\to cX}}{d\,\hat{t}} \frac{D_c^h(z)}{z}$$

Jet finders

What is a jet?

What is a jet?

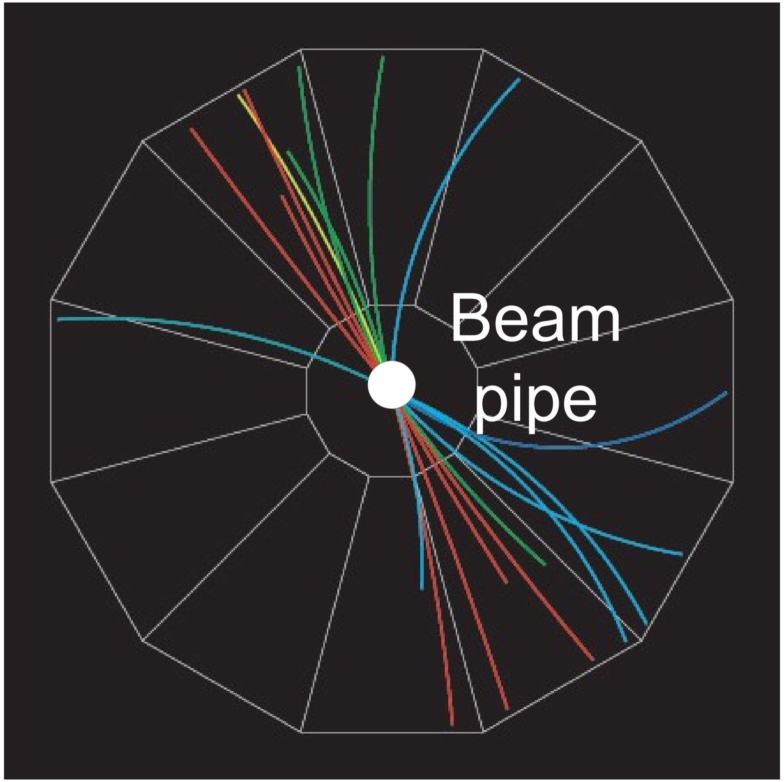
A measurement of a jet is a measurement of a parton.

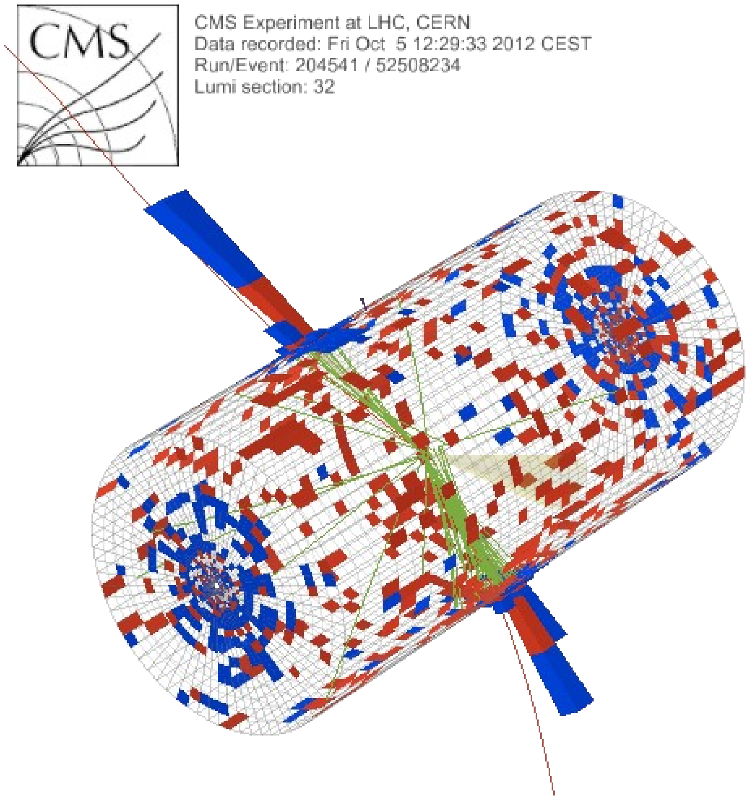
What is a jet?

~~A measurement of a jet is a measurement of a parton.~~

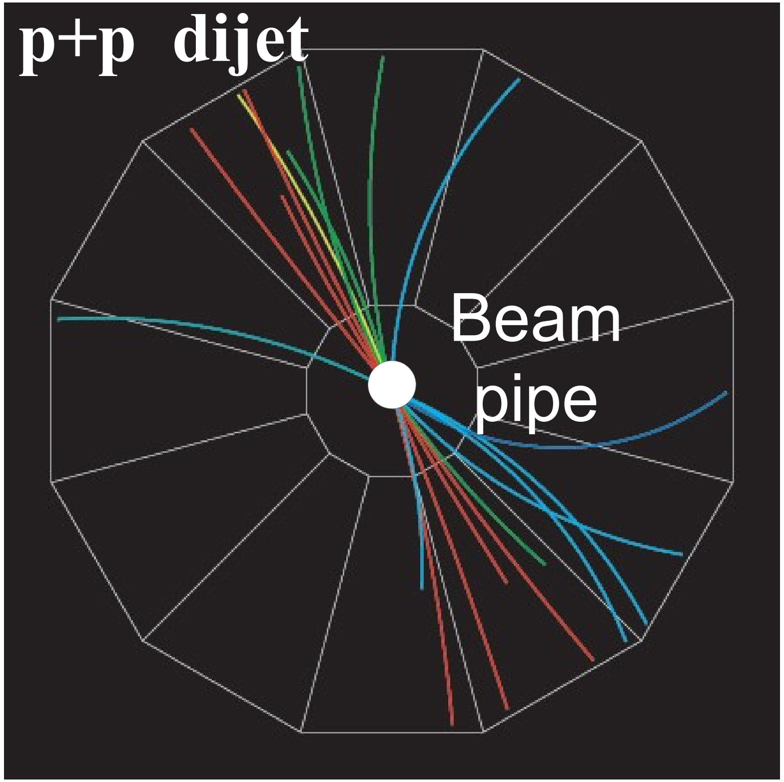
What is a jet?

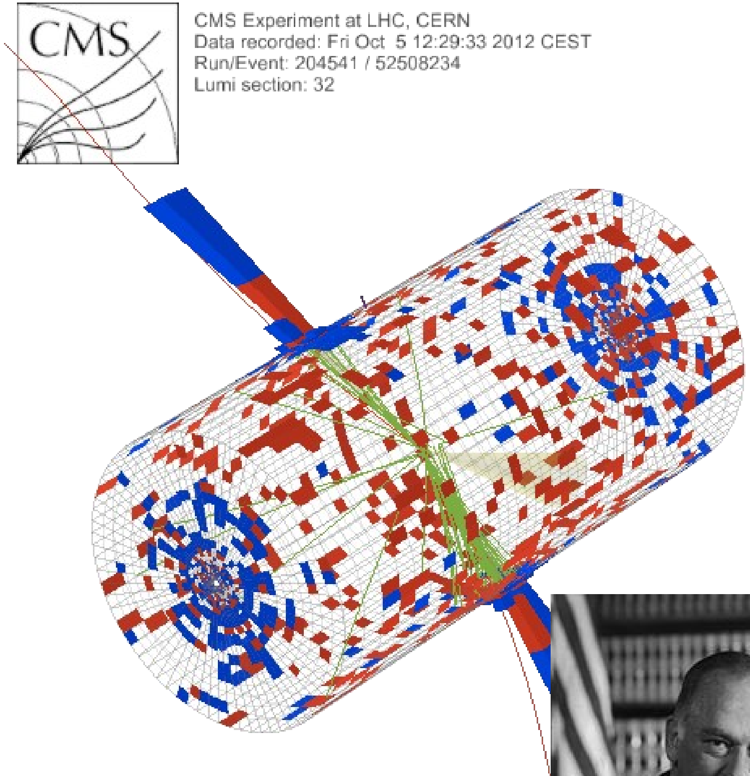
p+p dijet





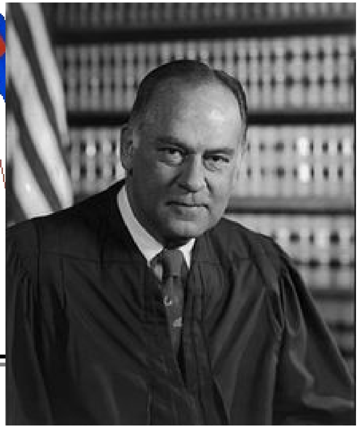
What is a jet?



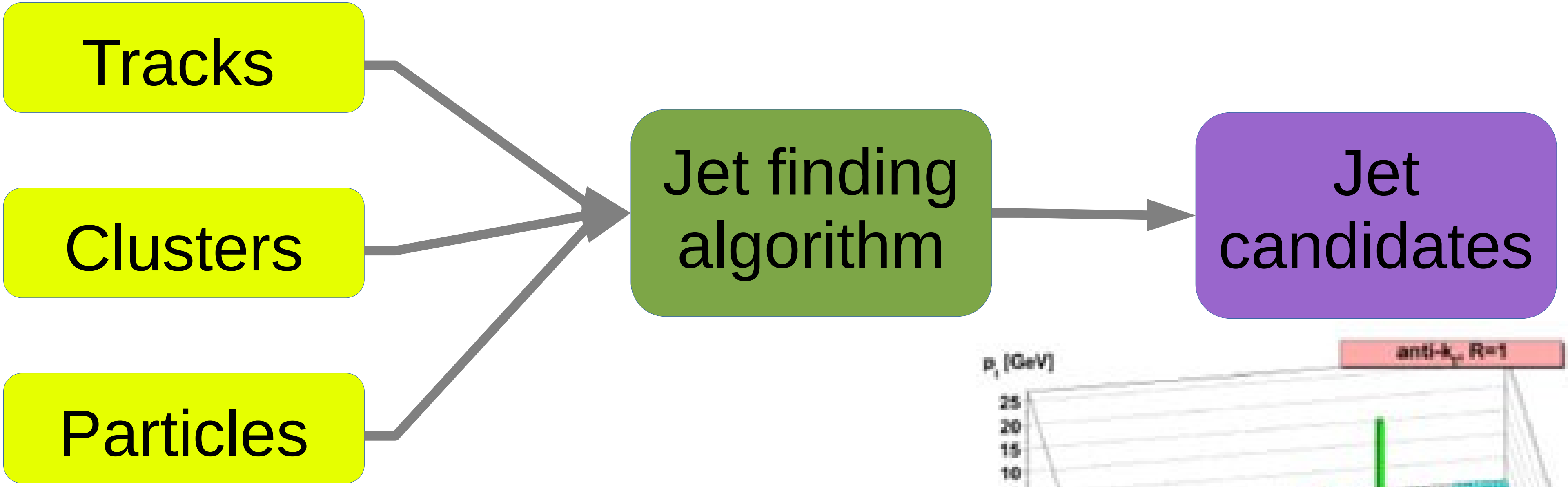


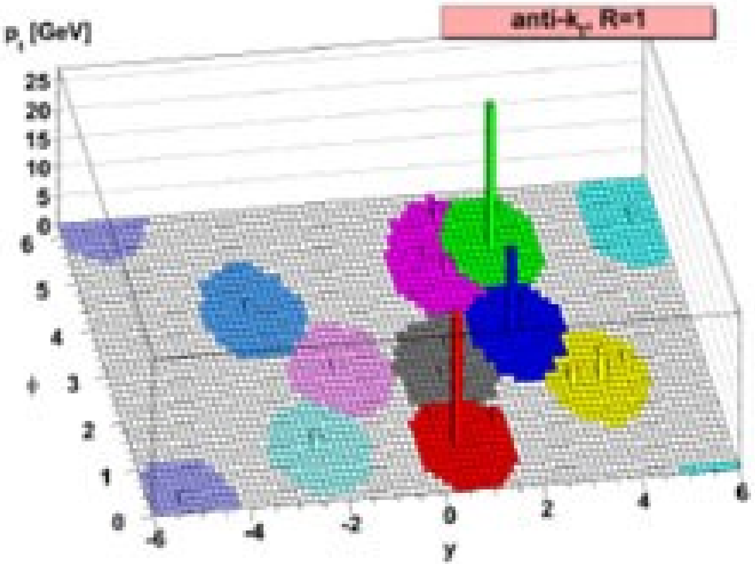
"I know it when I see it"

US Supreme Court Justice Potter Stewart, Jacobellis v. Ohio



Jet finding algorithms





- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input

Jet finding *in pp collisions*

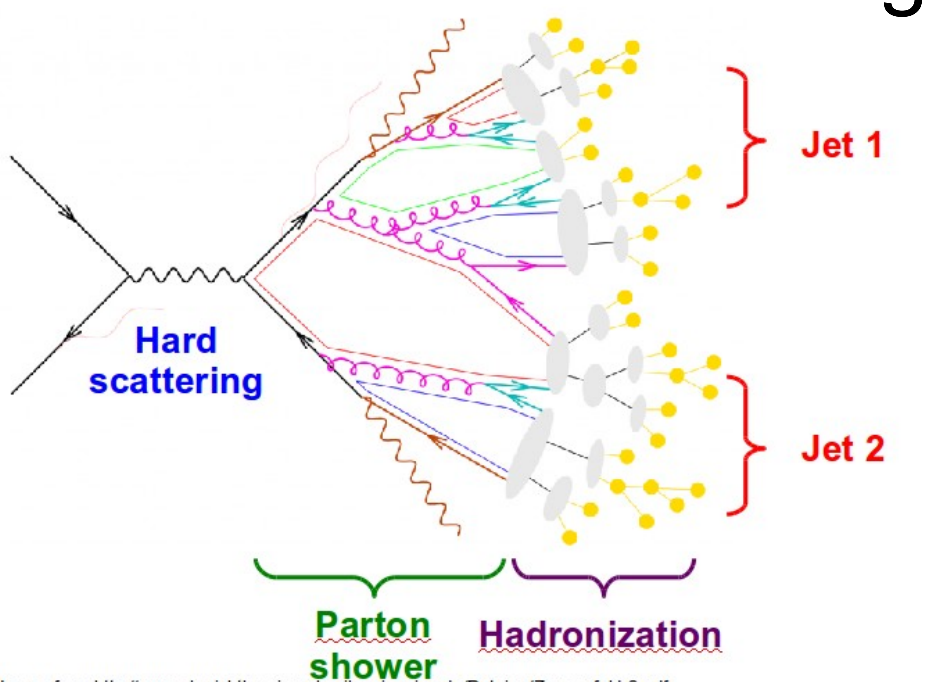


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Depends on hadronization
- Ideally
  - Infrared safe
  - Colinear safe

Snowmass Accord: Theoretical calculations and experimental measurements should use the same jet finding algorithm. Otherwise they will not be comparable.

Jets in principle

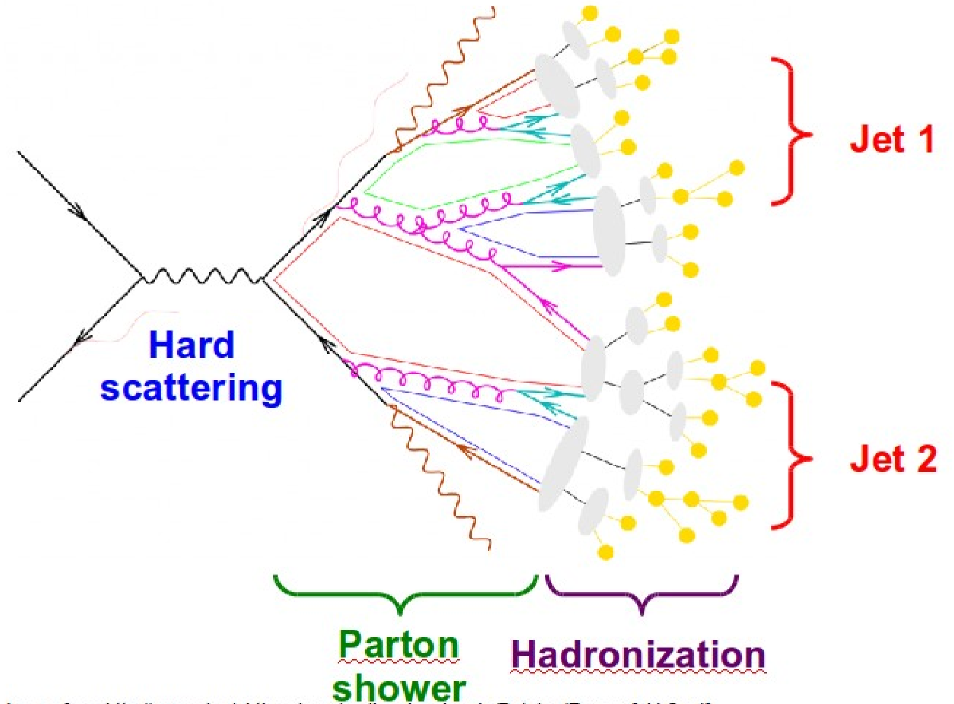
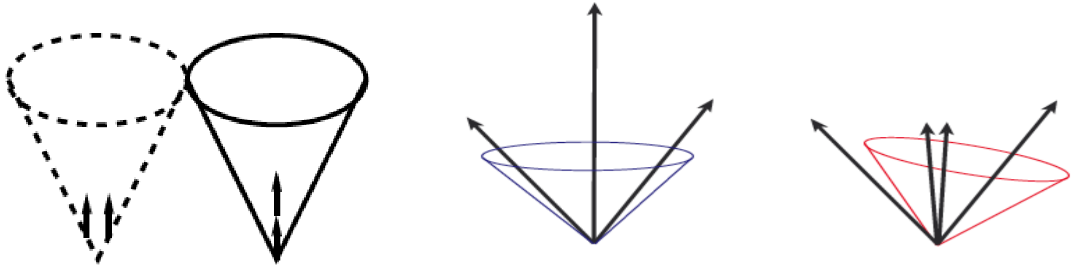
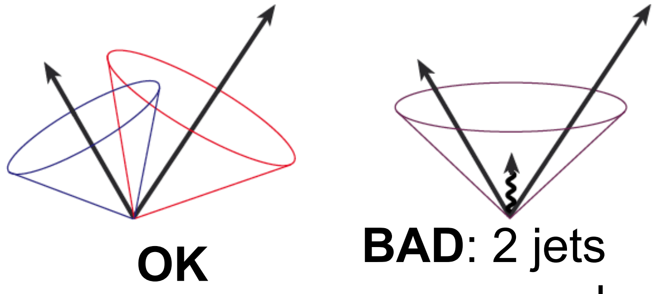


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and colinear safe





k_T jet finding algorithm

Particles, clusters

k_T algorithm

$$k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

- For all *i,j* calculate:

$$d_{ij} = min\left(p_{T,i}^2, p_{T,j}^2\right)\frac{\Delta R_{ij}^2}{R^2}$$

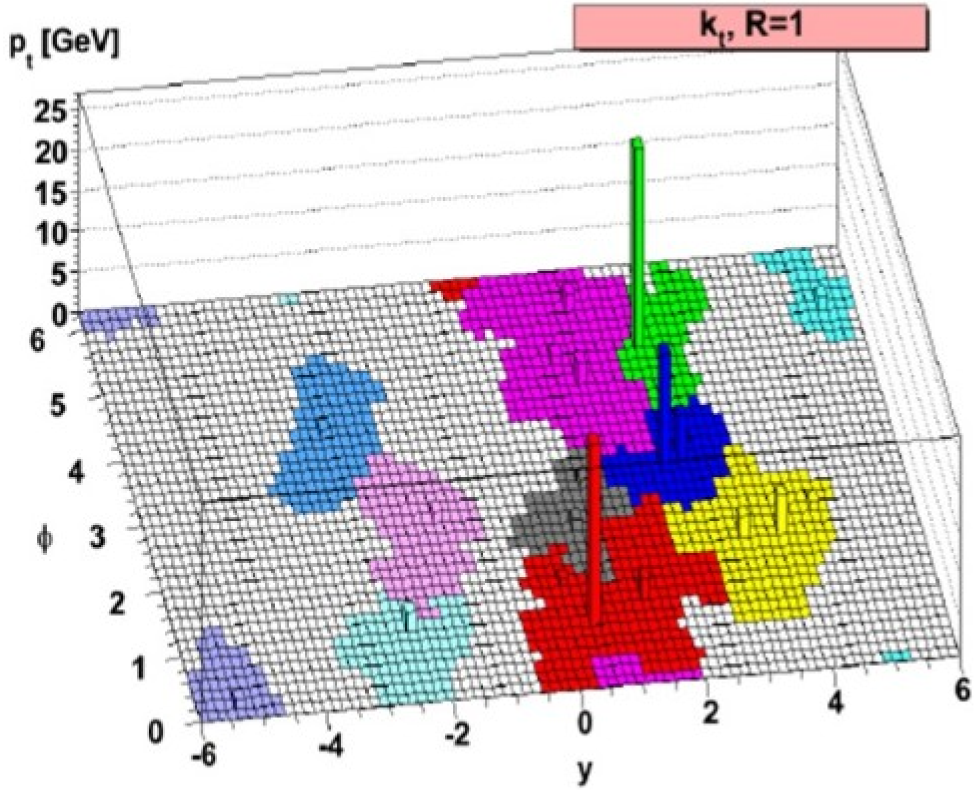
$$d_{iB} = p_{T,i}^2$$

- Combine smallest d_{ij}.

  If d_{iB} smallest, $d_{iB} \rightarrow$ jet

Repeat until no particles left

Jet candidates



anti-k_T jet finding algorithm

Particles, clusters

k_T algorithm

$$k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

- For all *i,j* calculate:

$$d_{ij} = min\left(p_{T,i}^{-2}, p_{T,j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

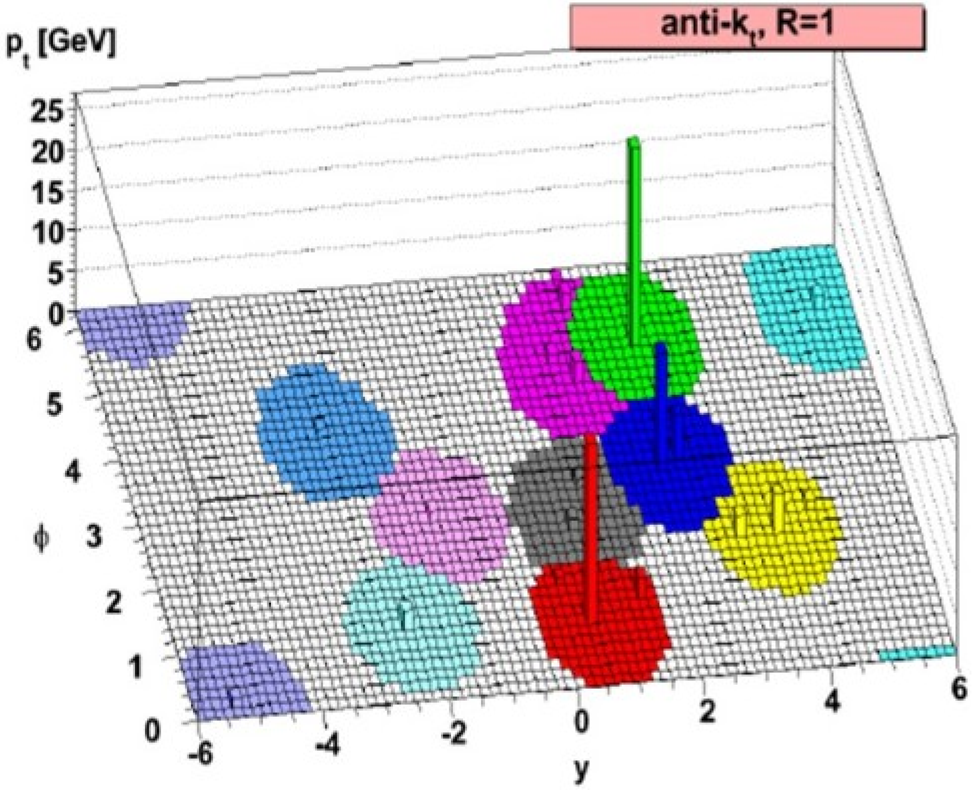
$$d_{iB} = p_{T,i}^{-2}$$

- Combine smallest d_{ij}.

  If d_{iB} smallest, $d_{iB} \rightarrow$ jet

Repeat until no particles left

Jet candidates



Cambridge/Aachen jet finding algorithm

Particles, clusters

k_T algorithm

$$k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

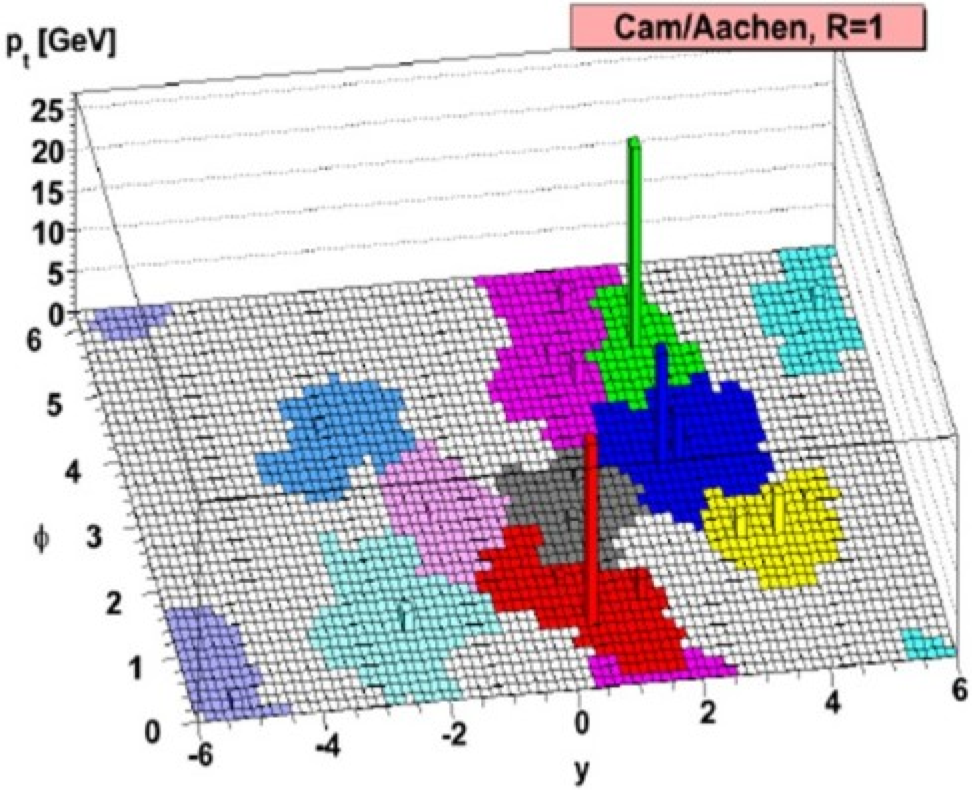
- For all *i,j* calculate:

$$d_{iB} = 1 \qquad d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$$

- Combine smallest d_{ij}.
  If d_{iB} smallest, $d_{iB} \rightarrow$ jet

Repeat until no particles left

Jet candidates

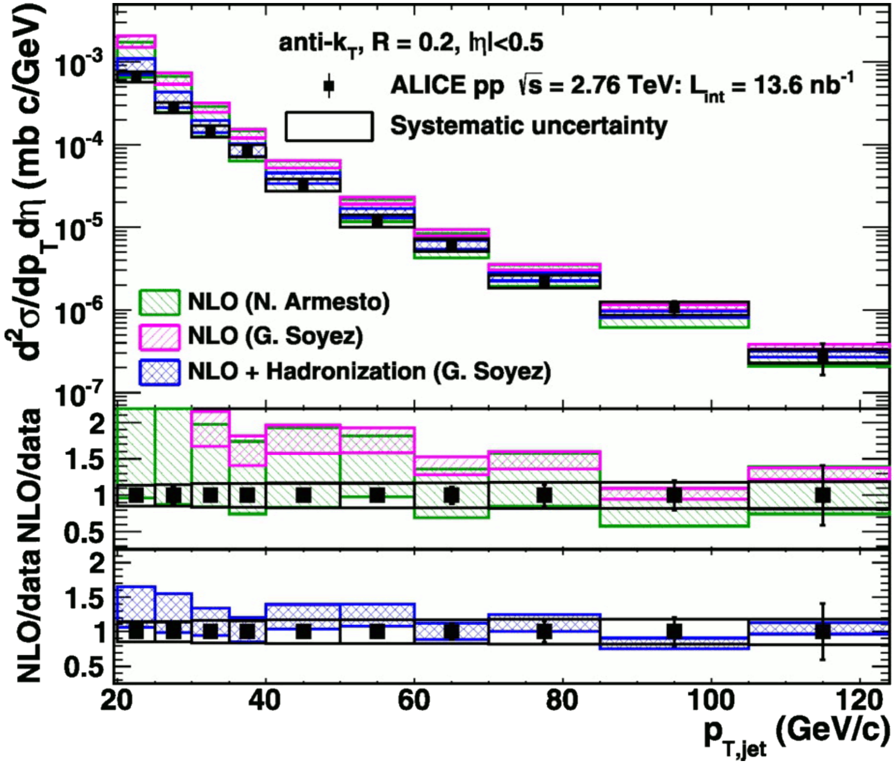


A jet is what a jet finder finds.

Jet cross-section in pp

√s = 2.76 TeV, R = 0.2 Inclusive

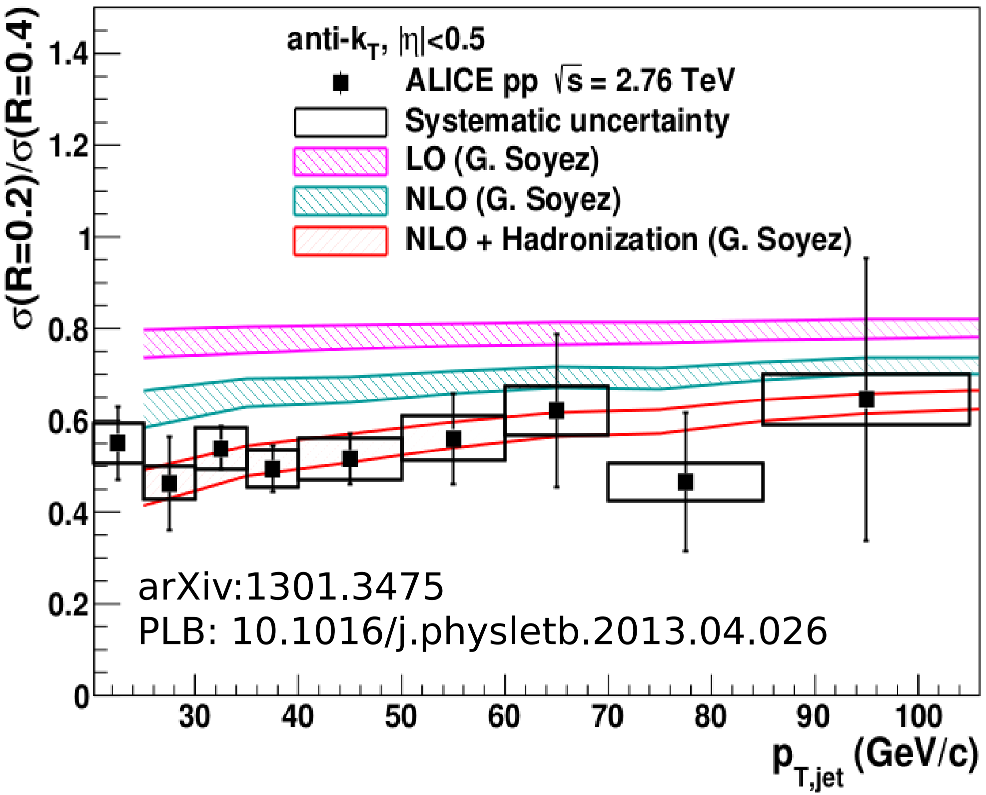
arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026

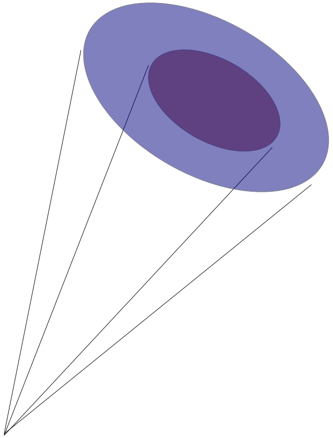


- Green and magenta bands: NLO on Parton level
- Blue band: NLO + hadronization
- Hadronization calculations necessary to describe data

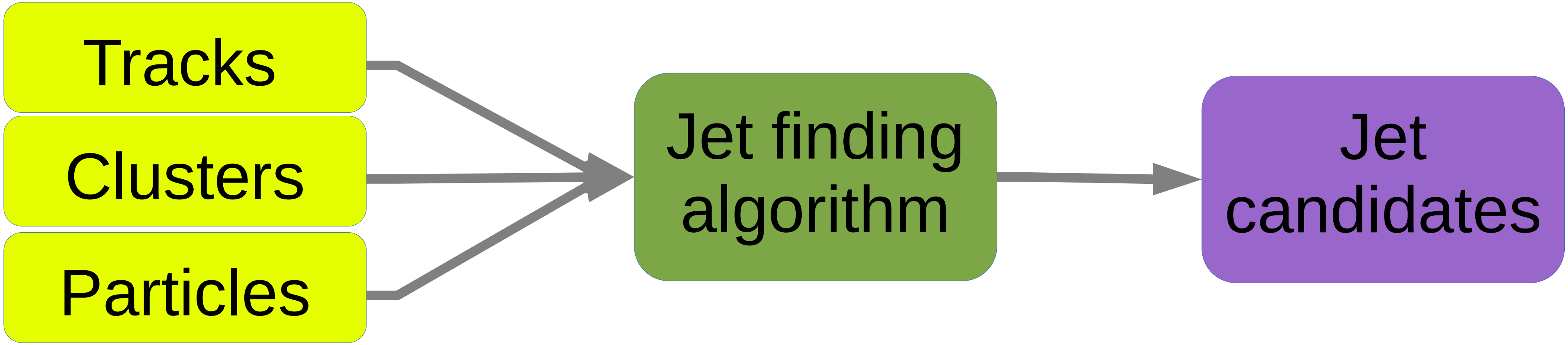
Jet ratios in pp

√s = 2.76 TeV, R = 0.2, 0.4 Inclusive





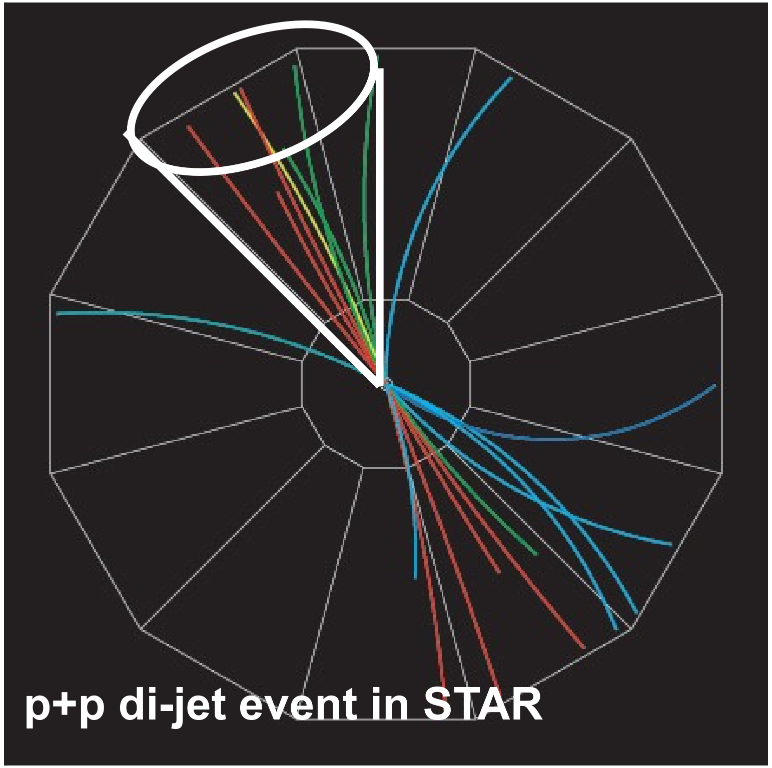
Mini-summary

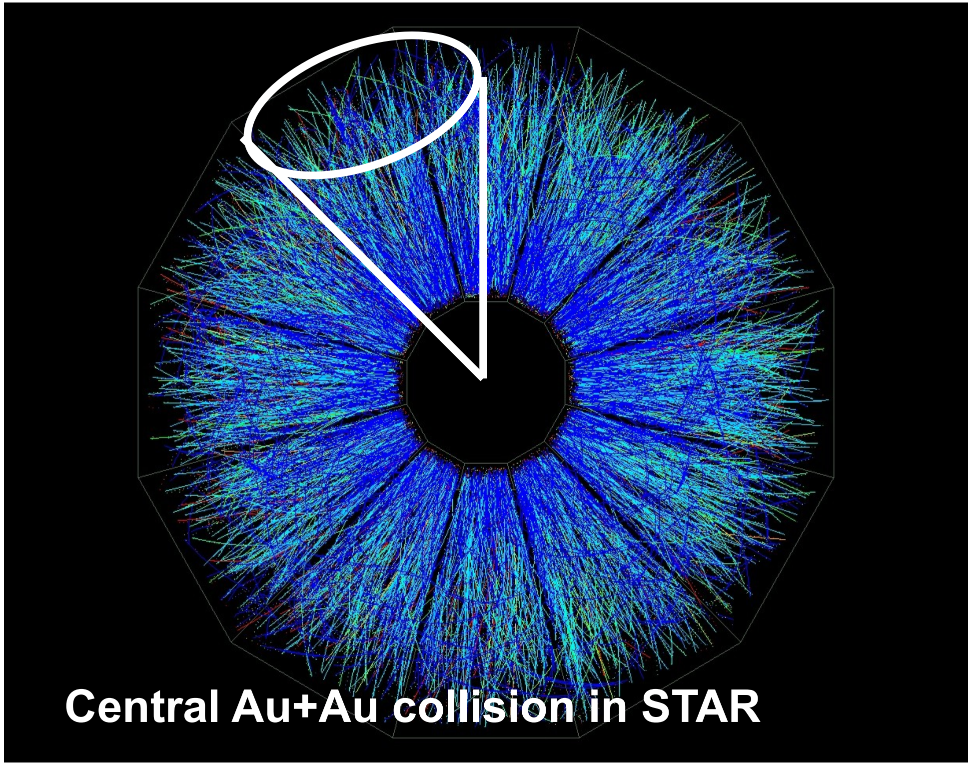


- Jets are not partons
- Good jet finders:
  - Infrared and colinear safe
  - k_T, anti-k_T, Cambridge/Aachen, SISCone
- Jet is defined by jet finder, its parameters
- PDFs, fragmentation functions non-perturbative
  → all jet measurements sensitive to somewhat non-perturbative effects
- Good agreement between theory and experiment

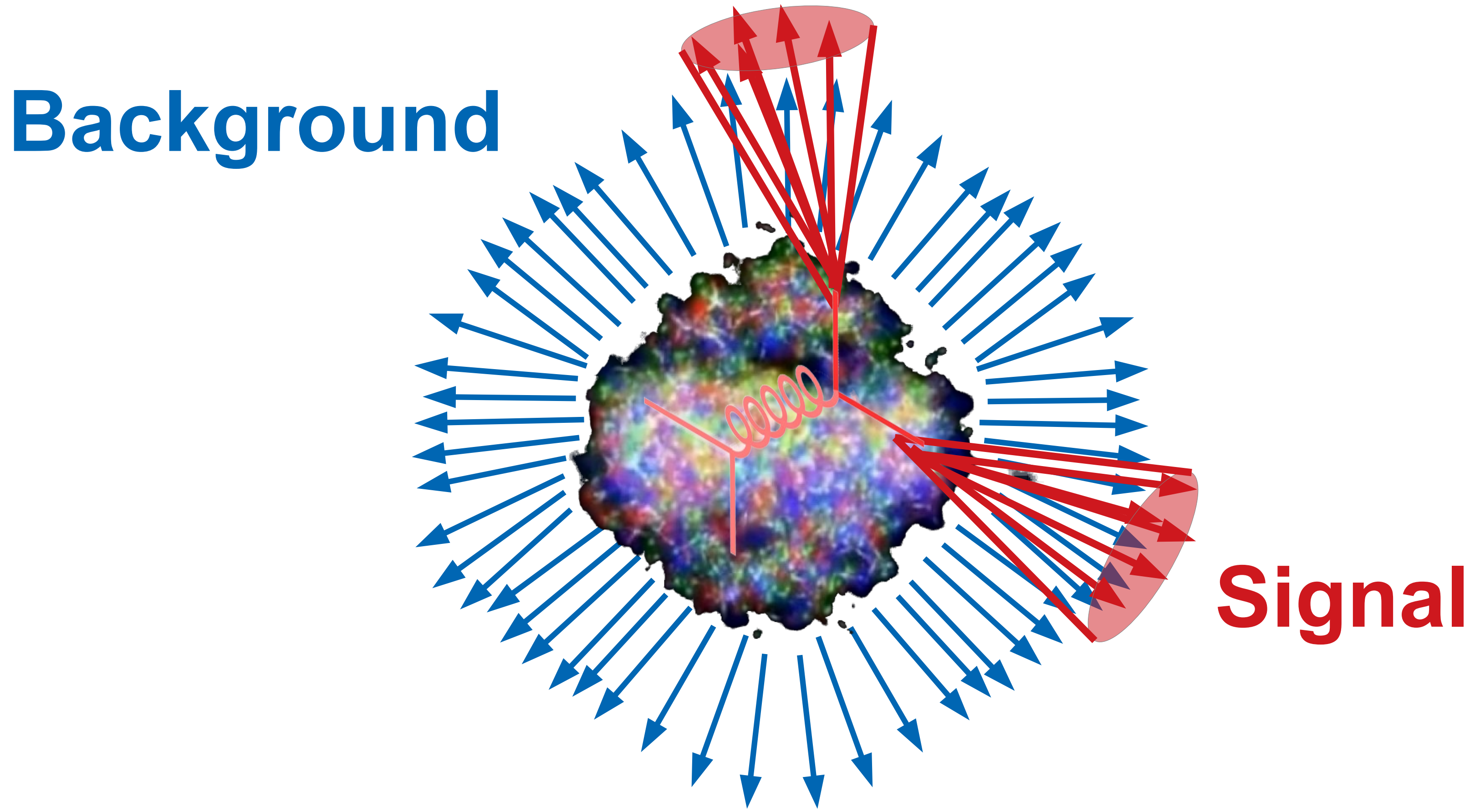
Jets in A+A collisions
What assumptions am I making?

p+p vs A+A



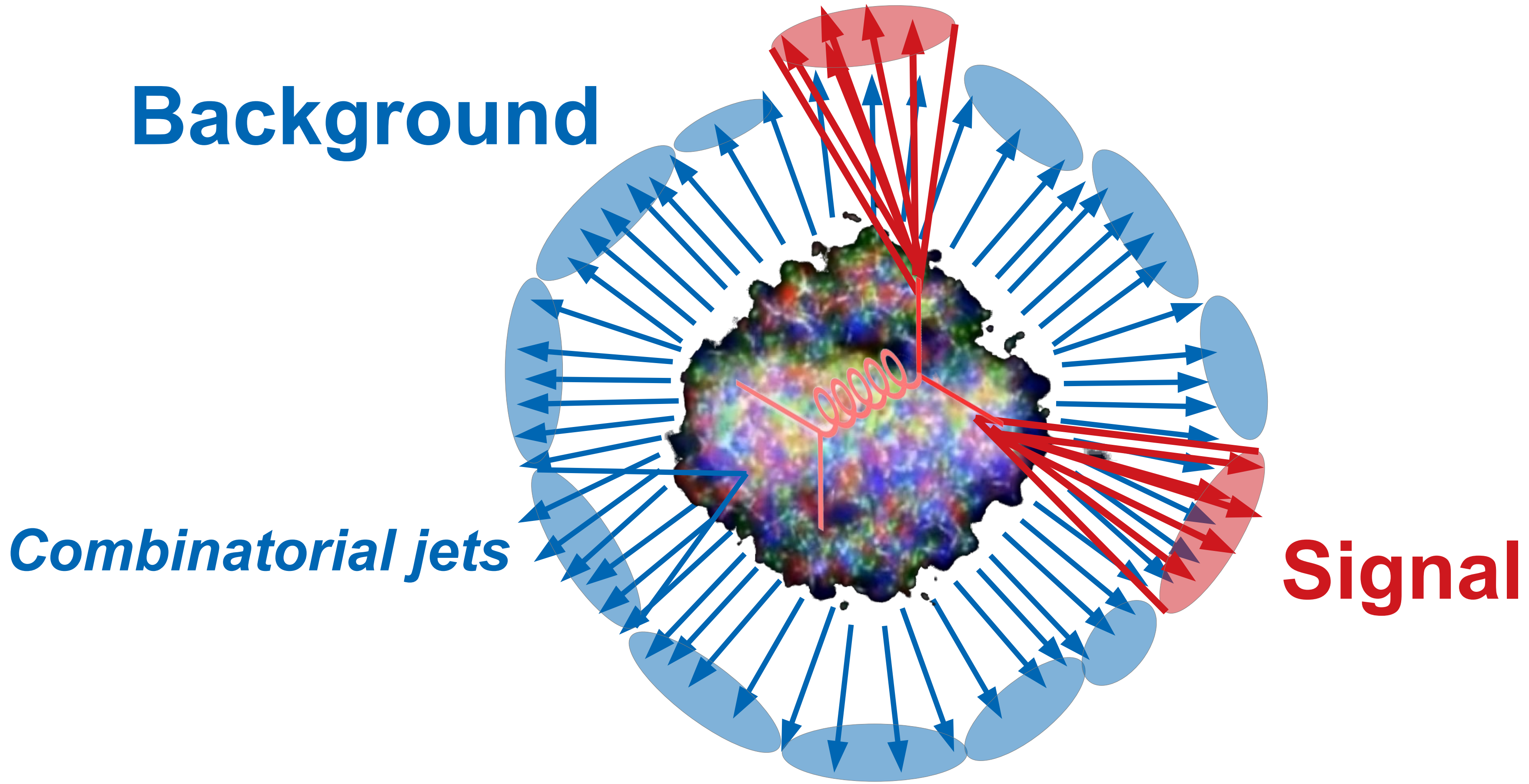


Signal vs Background:
The standard paradigm



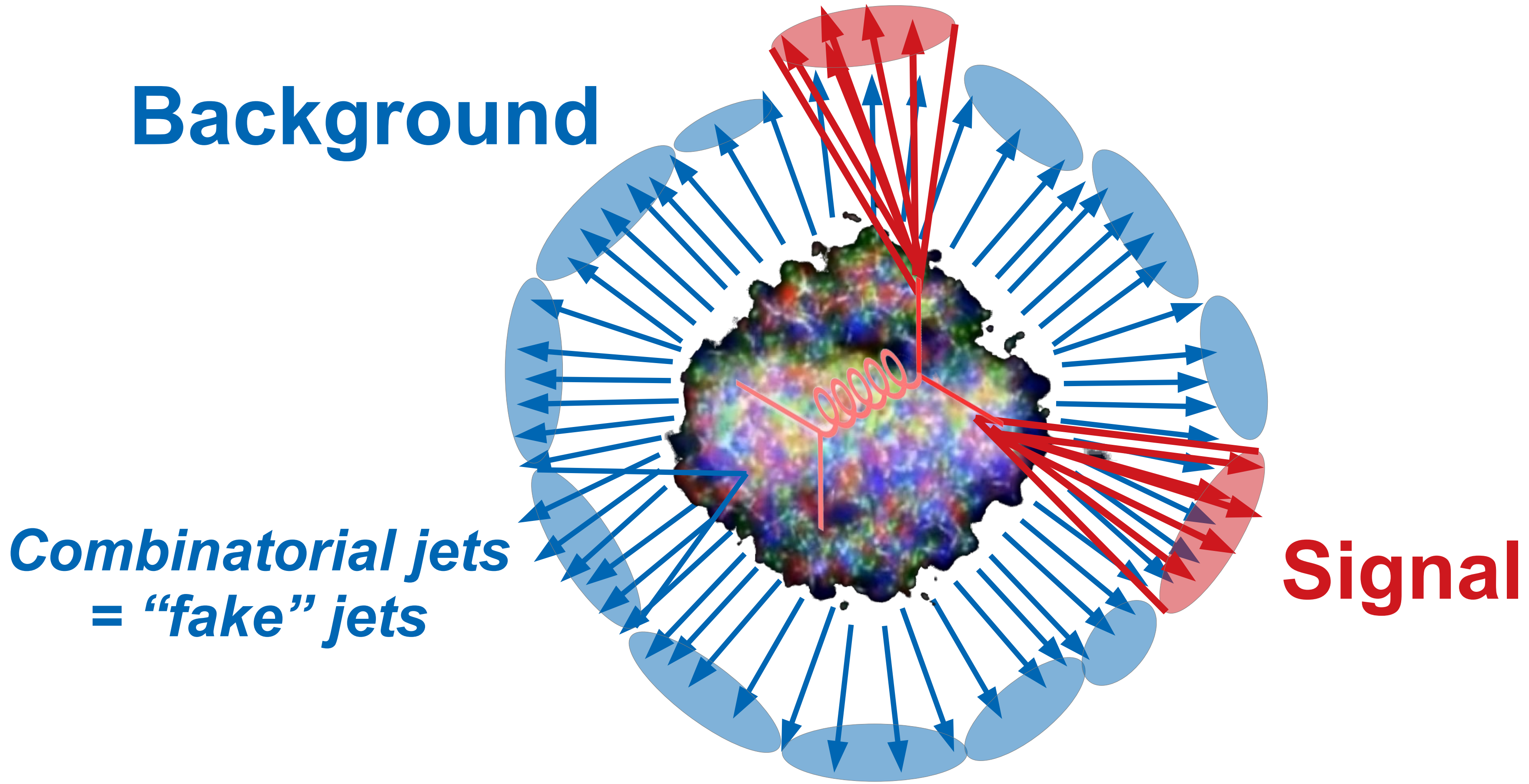
Signal vs Background:

The standard paradigm

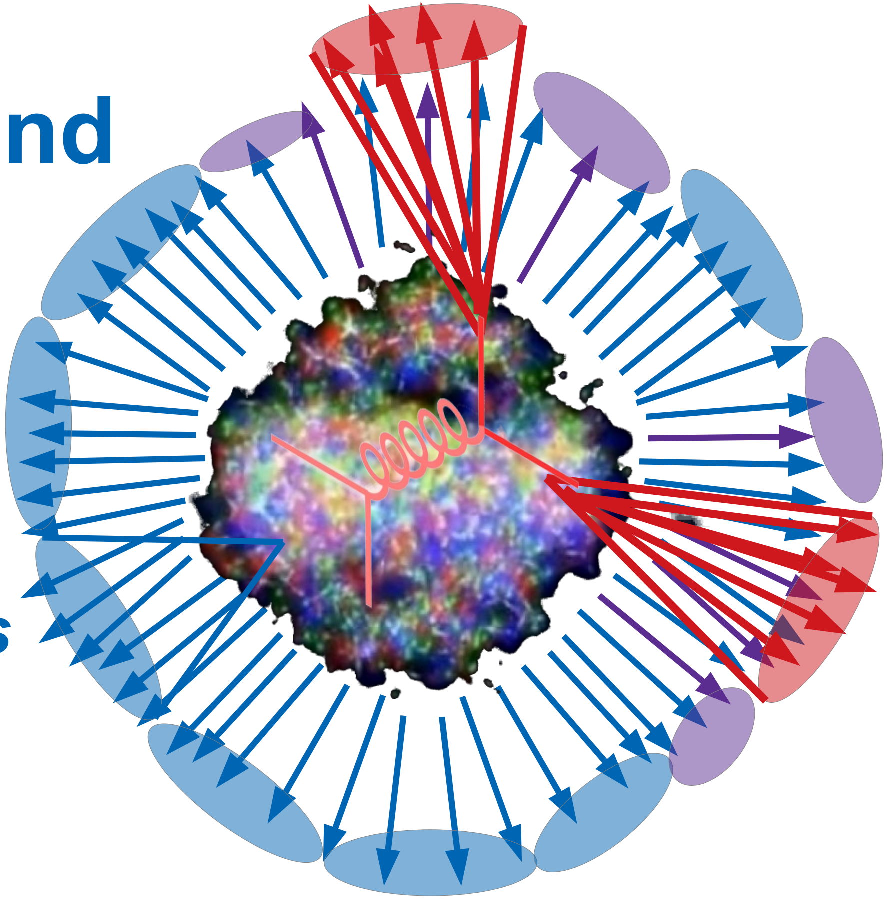


Signal vs Background:

The standard paradigm



Signal vs Background:
The standard paradigm



*Some gray areas

Jet finding in AA collisions

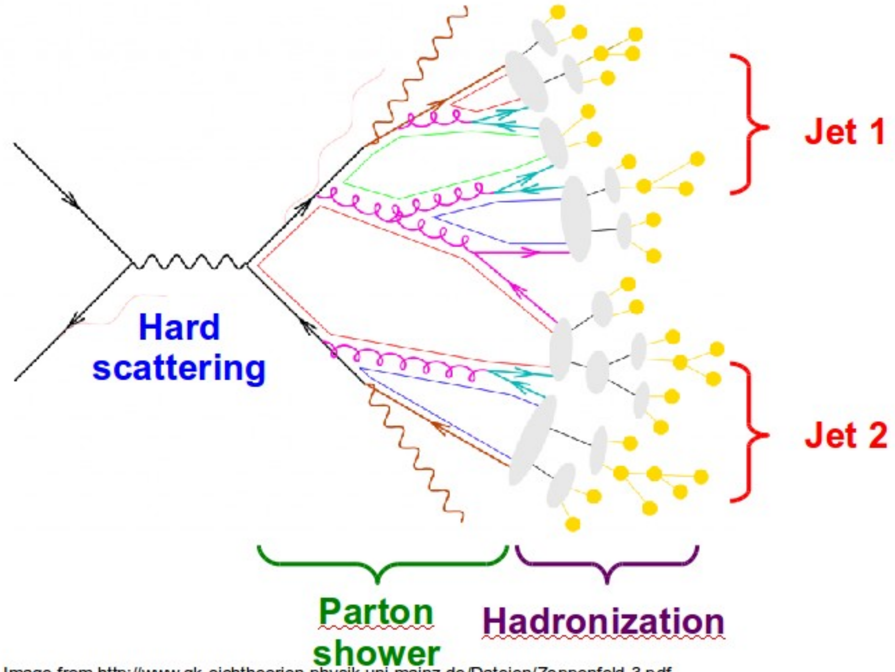
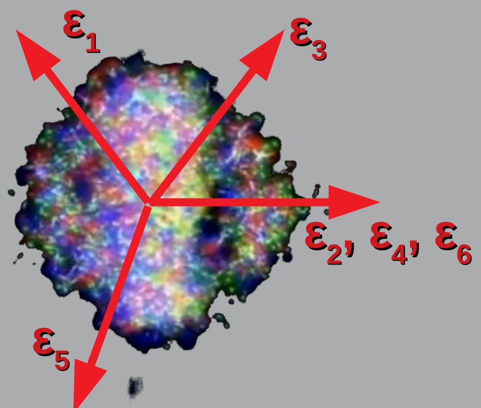


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Combinatorial jet candidates
- Energy smearing from background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets

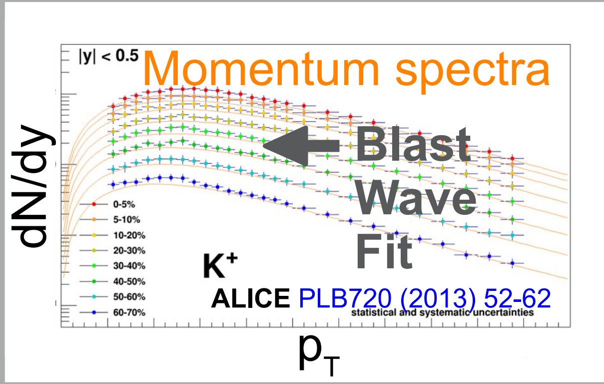
TennGen background generator

Event properties

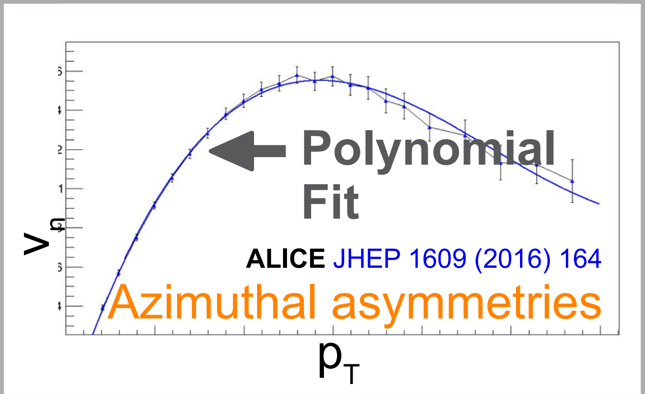


- Even event planes fixed at Ψ=0
- Odd planes at random φ
- Multiplies from ALICE PRC88 (2013) 044910

Track properties



→ Random p_T



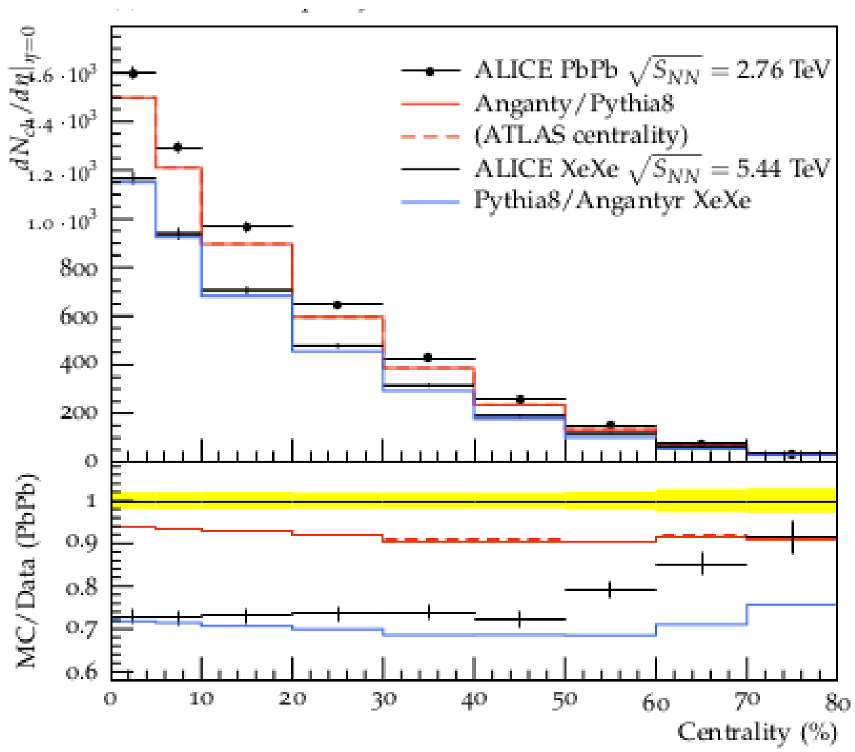
→ v_n → Random φ

No jets! No resonances
Emulates hydro correlations

PYTHIA Angantyr

JHEP (2018) 2018: 134

- Based on PYTHIA 8
  Sjöstrand, Mrenna & Skands,
  JHEP05 (2006) 026
  Comput. Phys. Comm. 178 (2008) 852.
- Based on Fritiof & wounded nucleons
- N-N collisions w/fluctuating radii → fluctuating σ



Lots of jets! And resonances!
No hydrodynamics, no jet quenching

Area-based background subtraction

Cacciari & Salam, PLB659:119–126,2008

Particles, clusters

k_T algorithm

$$k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

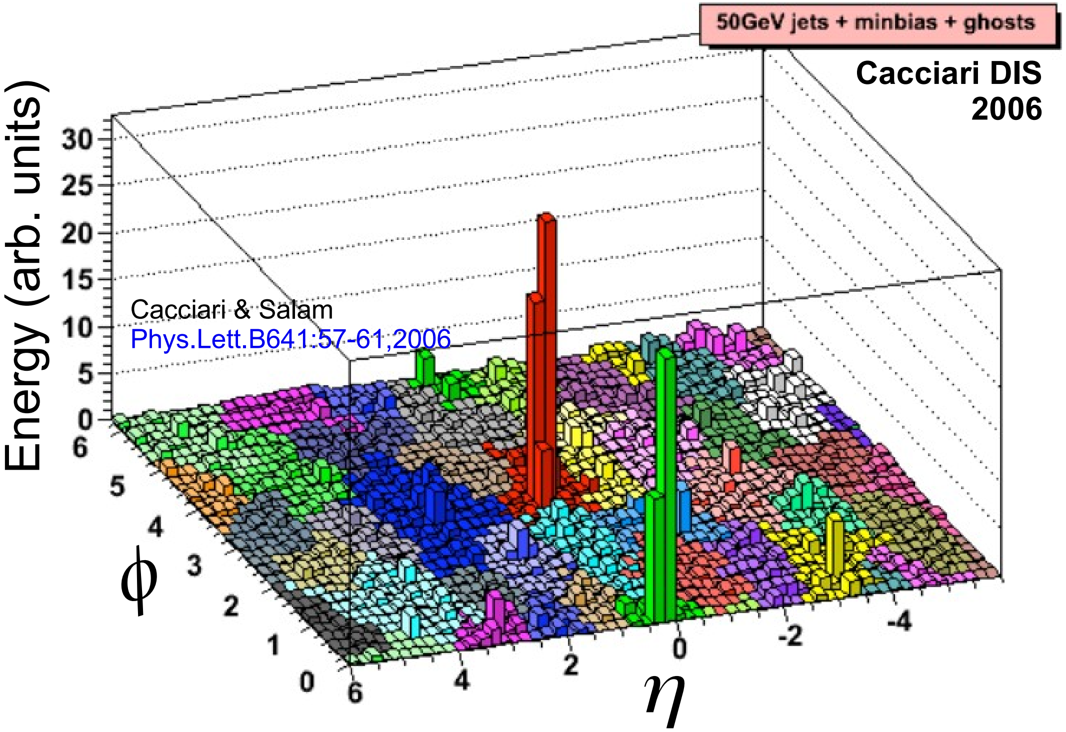
- For all *i,j* calculate:
  $$d_{ij} = min(p_{T,i}^2, p_{T,j}^2) \Delta R_{ij}^2$$
  $$d_{iB} = p_{T,i}$$
- Combine smallest d_{ij}.
  If d_{iB} smallest, $d_{iB} \rightarrow$ jet

Repeat until no particles left

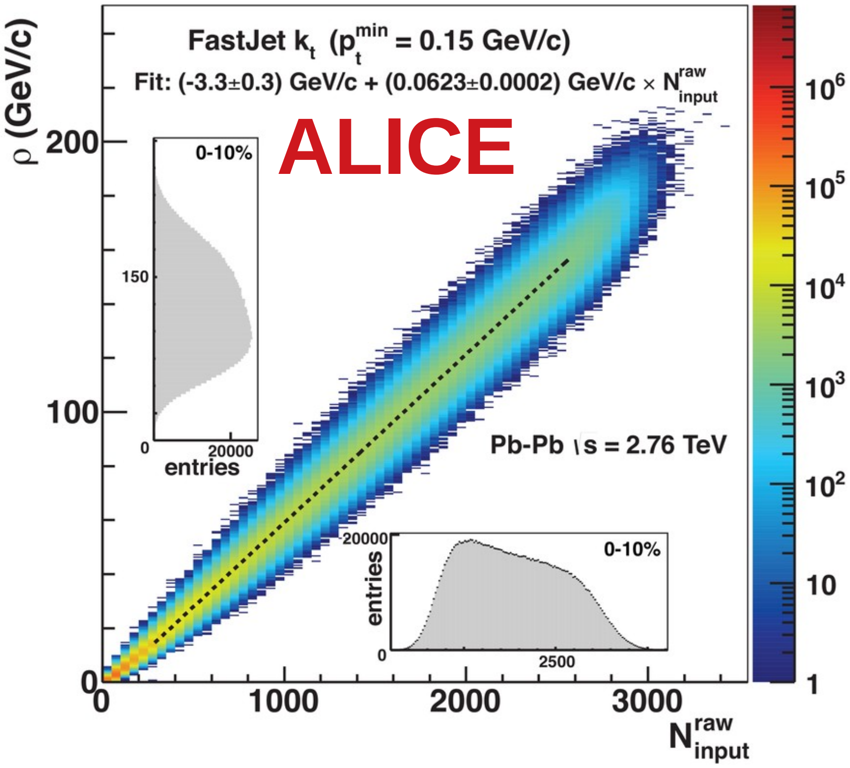
Jet candidates

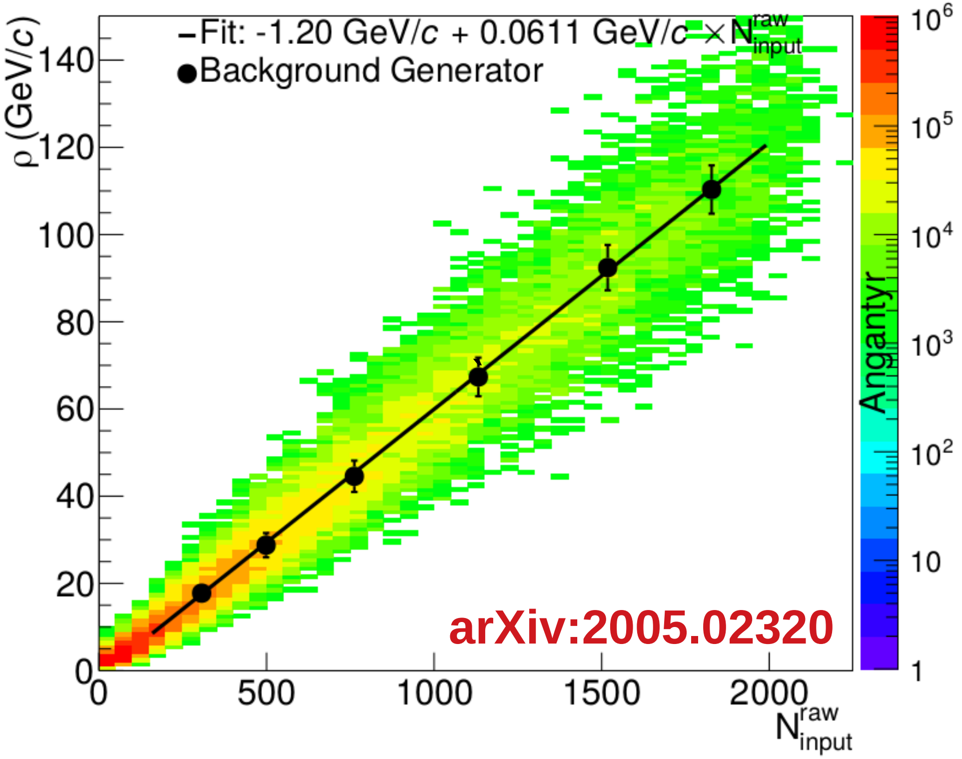
Median $\rho = p_T/A$

$$p_T^{jet} = p_T^{reco} - \rho_{median} A^{jet}$$

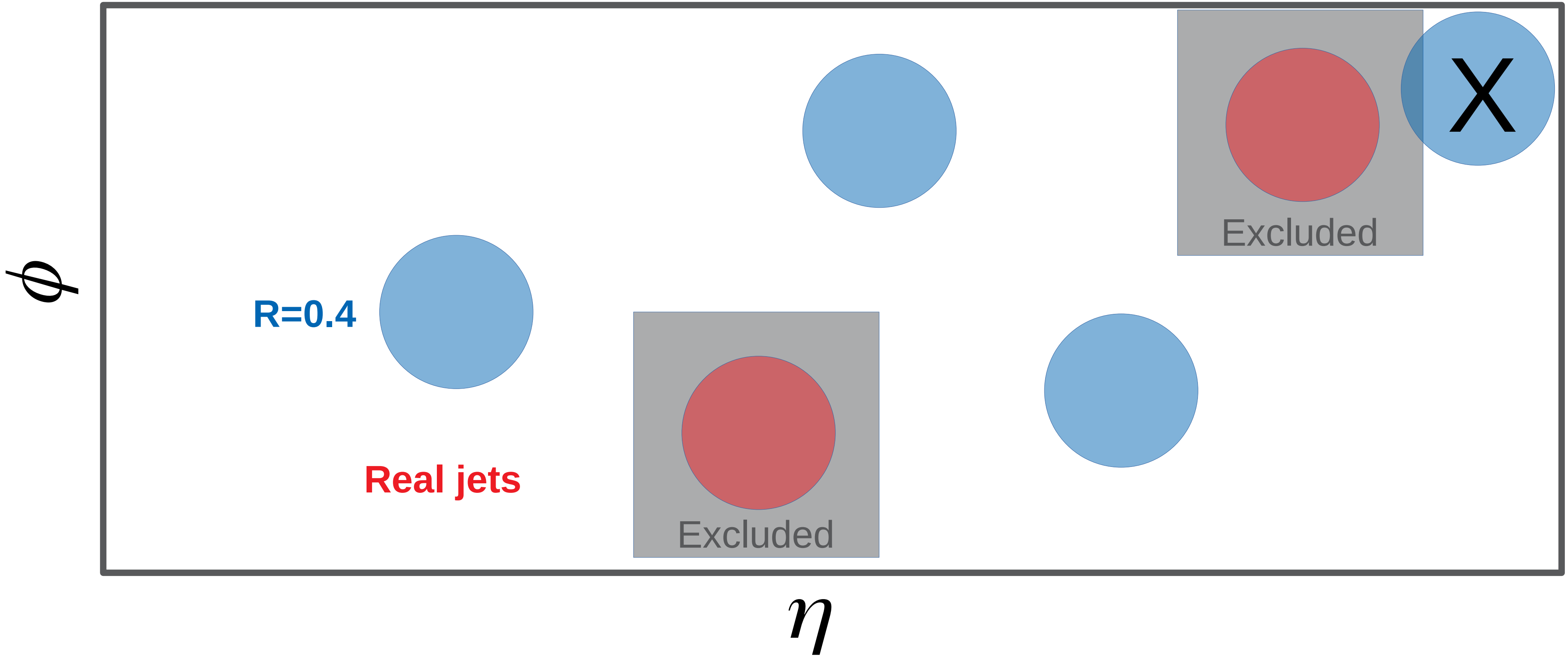


Background density ρ





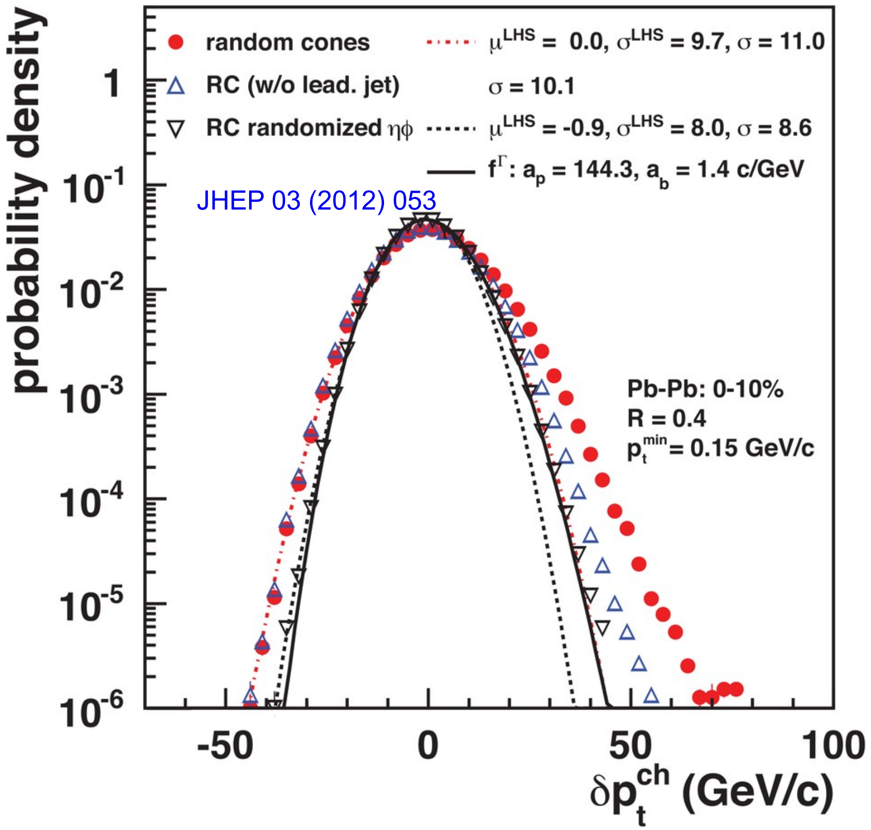
Random cones



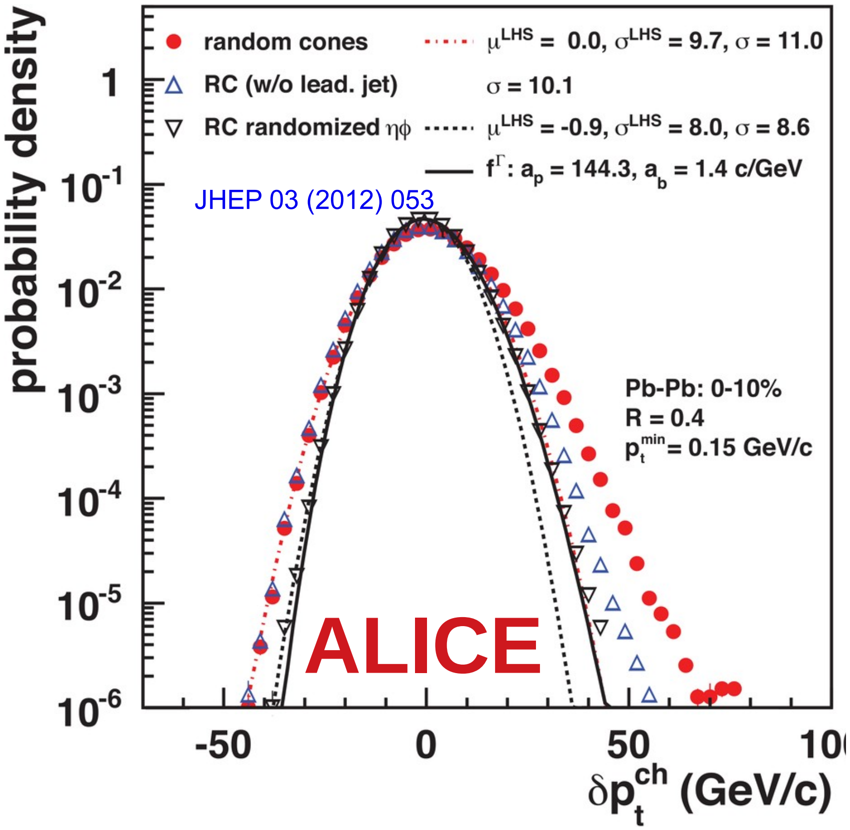
Random cones in ALICE

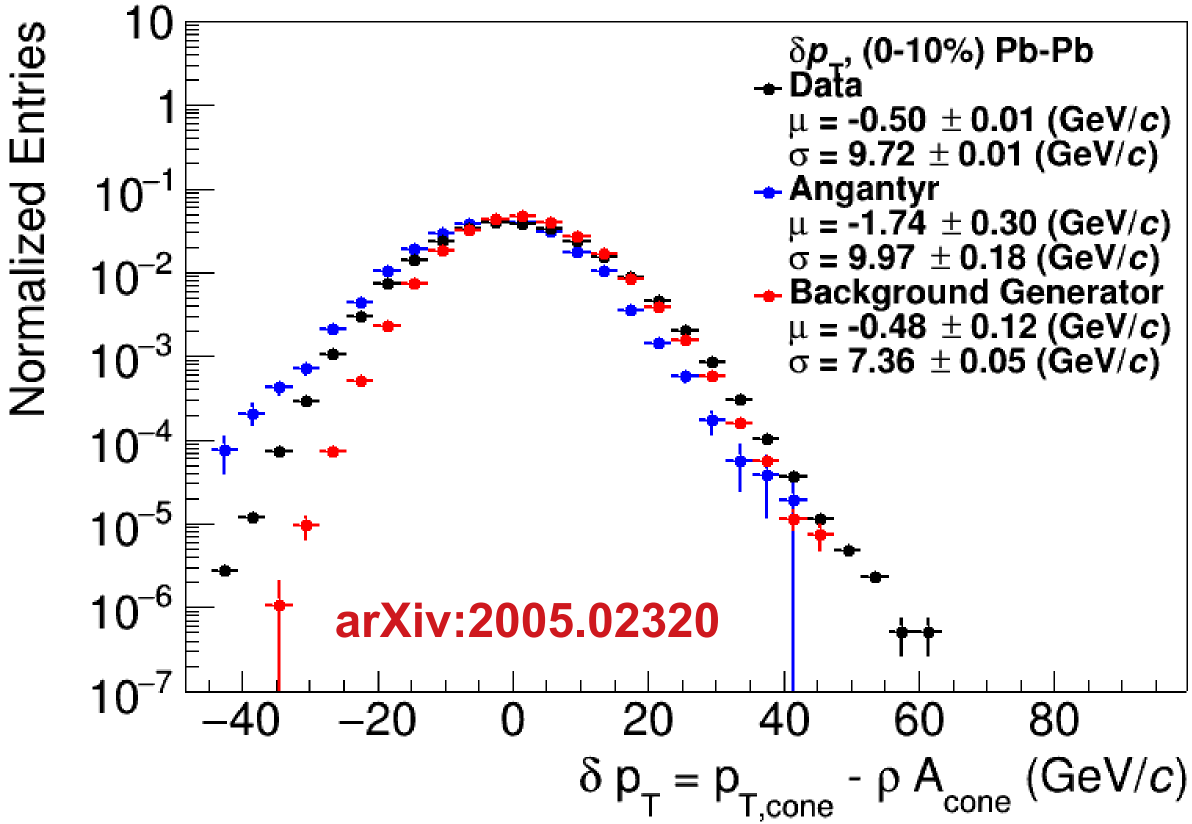
- Estimate ρ
  - k_T jet finder → jet candidates
  - $\rho = \text{Median}(p_T/A)$
- Draw Random cone

$$\delta p_T = p_T^{reco} - \rho A$$



Random cones





Shape of width of the distribution

Single particle spectra

$$f_\Gamma(p_T, p, b) = \frac{b}{\Gamma(p)} (b\, p_T)^{p-1} e^{-bx}$$

$$\frac{dN}{dy} \propto f_\Gamma(p_T, 2, b) = b^2\, p_T\, e^{-k\, p_T}$$

$$\mu_{p_T} = \frac{p}{b}, \sigma_{p_T} = \frac{\sqrt{p}}{b}$$

Tannenbaum, PLB(498),1–2,Pg.29-34(2001)

Σp_T of N particles → N-fold convolution:

$$f_N(p_T, p, b) = f_\Gamma(p_T, Np, b) \qquad \frac{dpT^{total}}{dy} \propto f_N(p_T, Np, b)$$

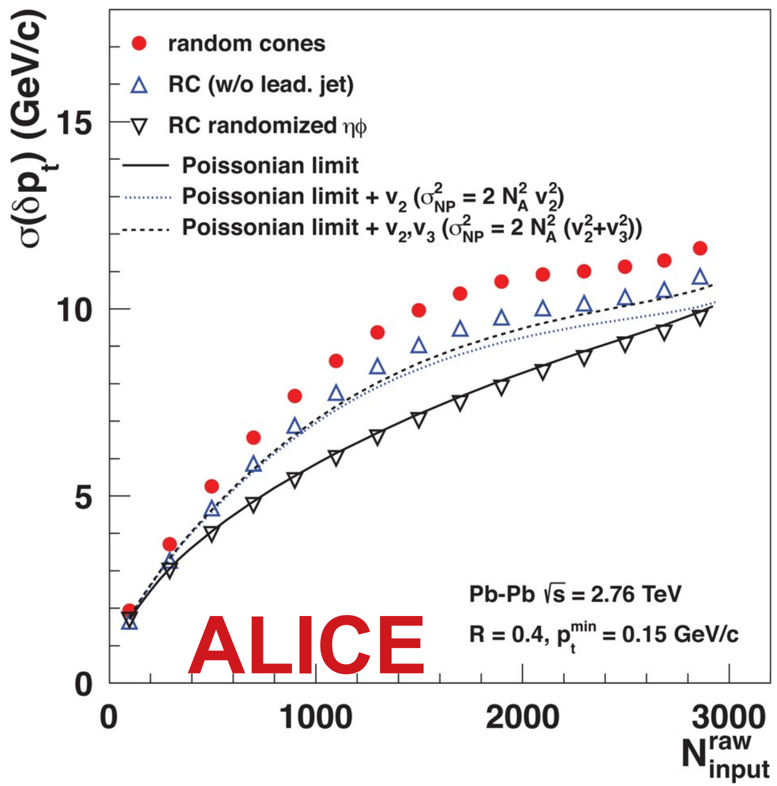
$$N = \frac{N_{total}}{A_{total}} \pi R^2 \quad \mu_{total} = \frac{Np}{b} = N\, \mu_{p_T}, \sigma_{total} = \frac{\sqrt{Np}}{b} = \sqrt{N}\, \sigma_{p_T}$$

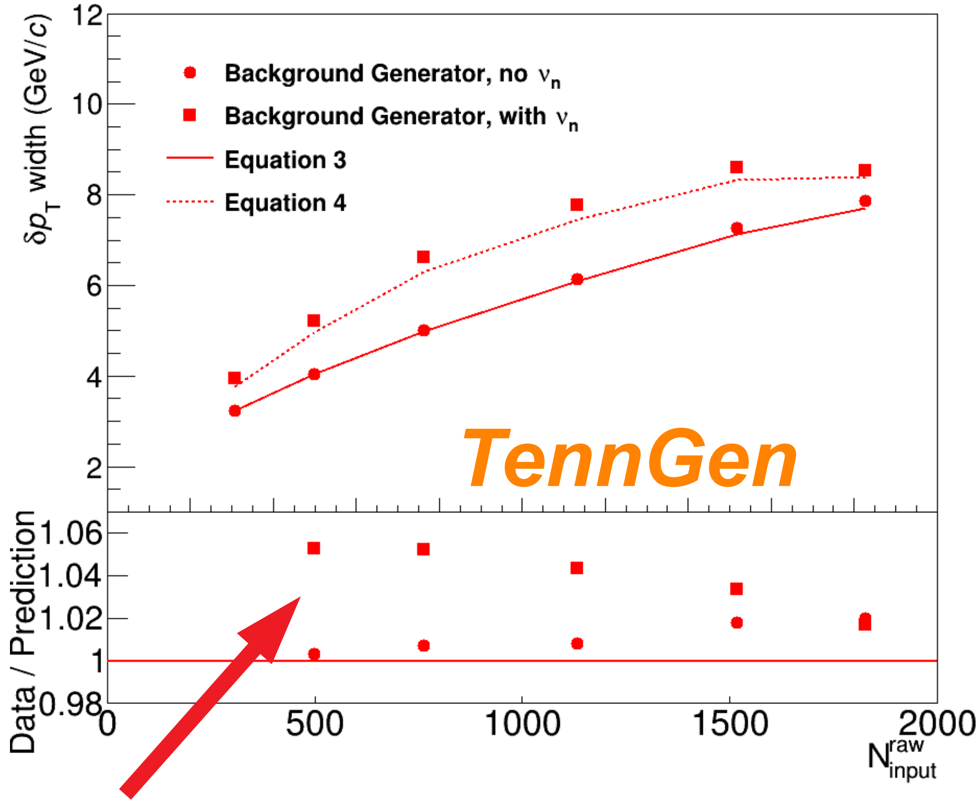
Add Poissonian fluctuations in N: $\sigma_{total} = \sqrt{N\, \sigma_{p_T}^2 + N\, \mu_{p_T}^2}$

Add non-Poissonian fluctuations in N due to flow

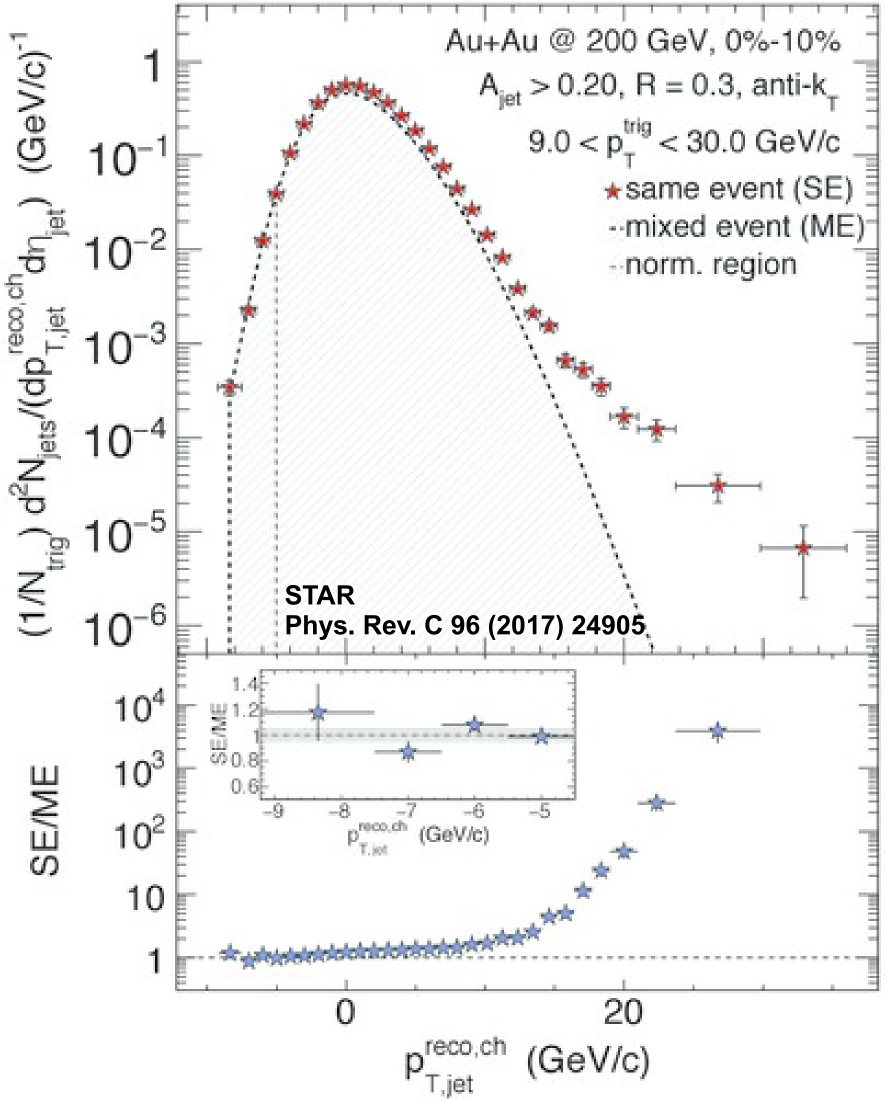
$$\sigma_{total} = \sqrt{N\, \sigma_{p_T}^2 + (N + 2 \sum_n v_n^2) \mu_{p_T}^2}$$

Width vs multiplicity





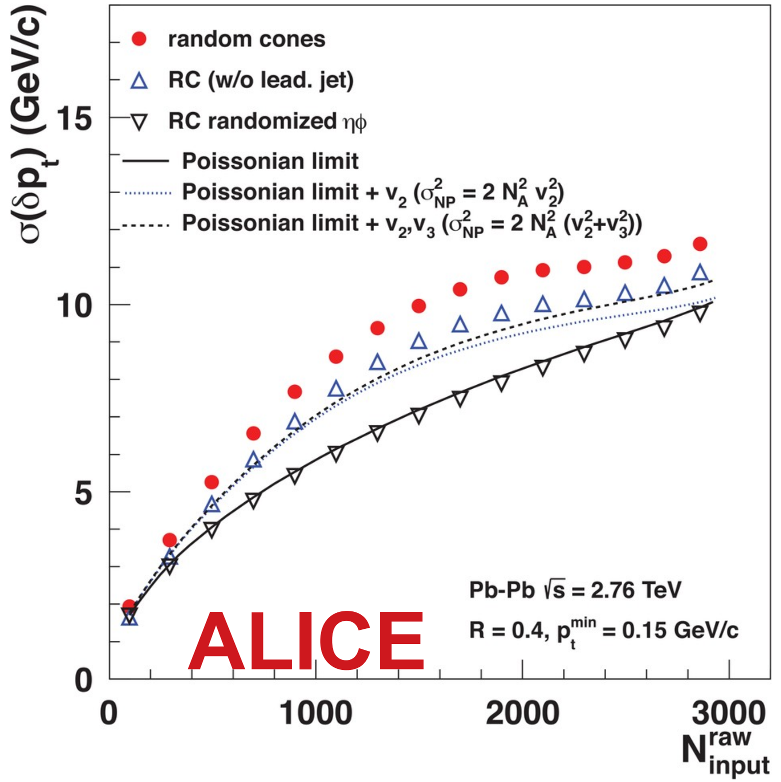
Small deviations

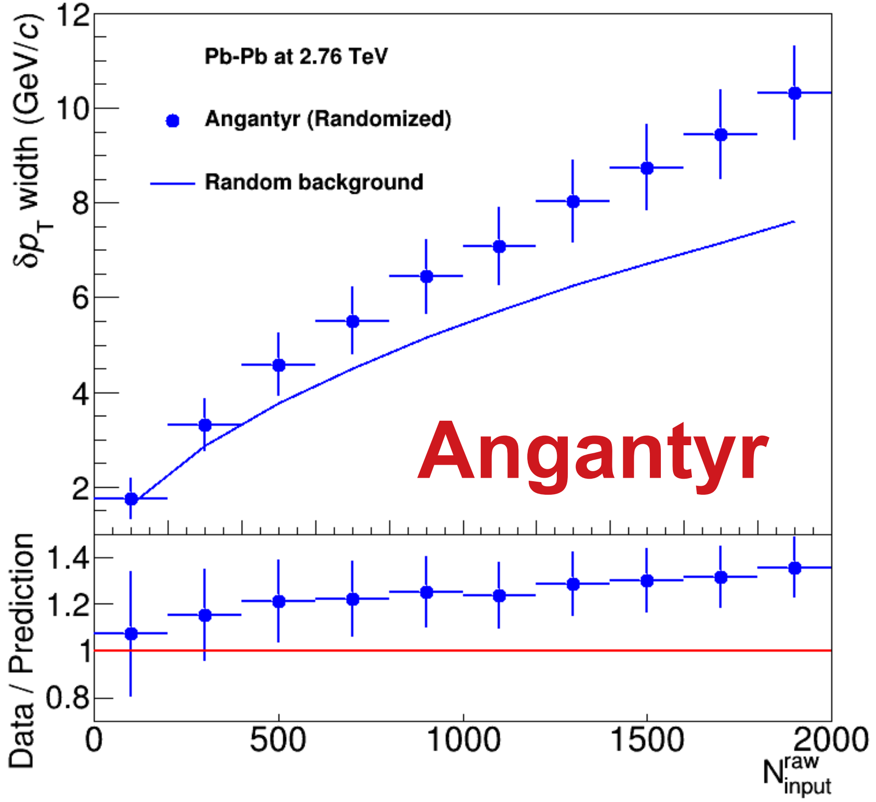


Mixed events

- Gets background up to a normalization factor
- Good agreement with the data… but 20% discrepancies still within uncertainties
- In measurement with background suppressed (h-jet correlations)
- Did not see such agreement at the LHC

Width vs multiplicity





Doesn’t go away with random track orientation!

Shape of width of the distribution

Single particle spectra

$$f_\Gamma(p_T, p, b) = \frac{b}{\Gamma(p)} (b\, p_T)^{p-1} e^{-bx}$$

$$\frac{dN}{dy} \propto f_\Gamma(p_T, 2, b) = b^2 p_T e^{-k p_T}$$

$$\mu_{p_T} = \frac{p}{b}, \sigma_{p_T} = \frac{\sqrt{p}}{b}$$

Tannenbaum, PLB(498),1–2,Pg.29-34(2001)

Assumes shape

Σp_T of N particles → N-fold convolution:

$$f_N(p_T, p, b) = f_\Gamma(p_T, Np, b) \qquad \frac{dpT^{total}}{dy} \propto f_N(p_T, Np, b)$$

$$N = \frac{N_{total}}{A_{total}} \pi R^2 \qquad \mu_{total} = \frac{Np}{b} = N \mu_{p_T}, \sigma_{total} = \frac{\sqrt{Np}}{b} = \sqrt{N} \sigma_{p_T}$$

Add Poissonian fluctuations in N: $\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + N \mu_{p_T}^2}$

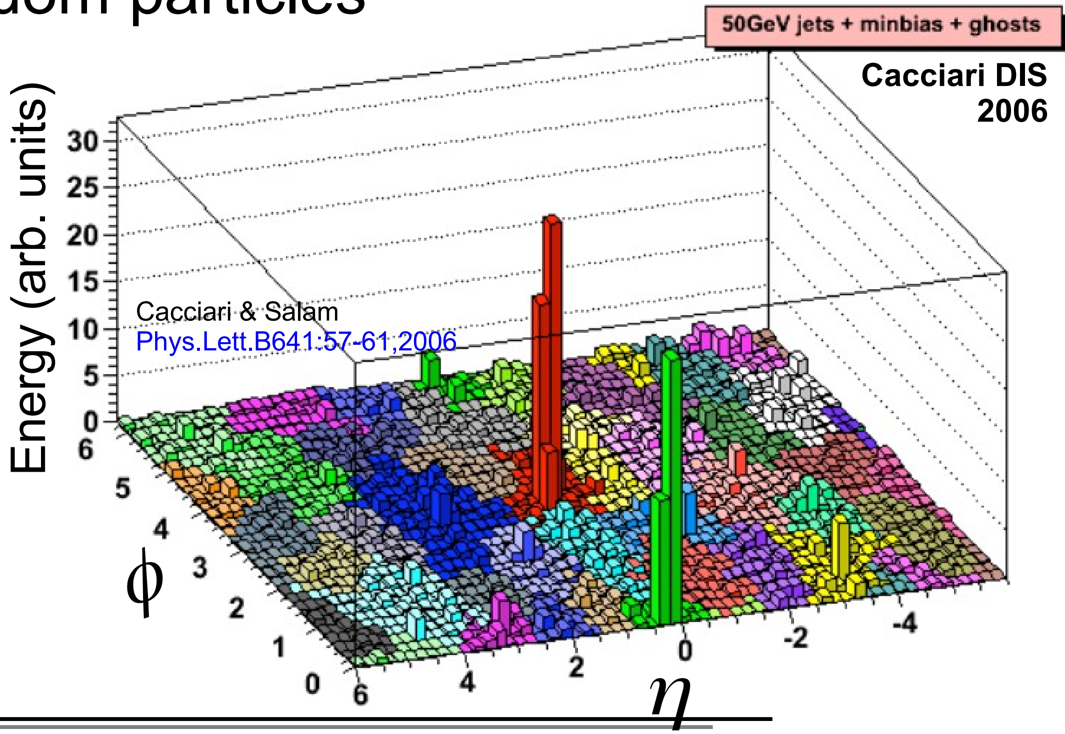
Add non-Poissonian fluctuations in N due to flow

$$\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + \left(N + 2 \sum_n v_n^2\right) \mu_{p_T}^2}$$

Assumes uncorrelated number fluctuations

Mini-summary

- Jet finders put all input clusters, tracks in a jet candidate
- Background is *dominated* by random particles
  - But 5% effects from flow
- Models have background too!
  - And it doesn't agree with data!
  - Sensitive to multiplicity, shape of spectrum

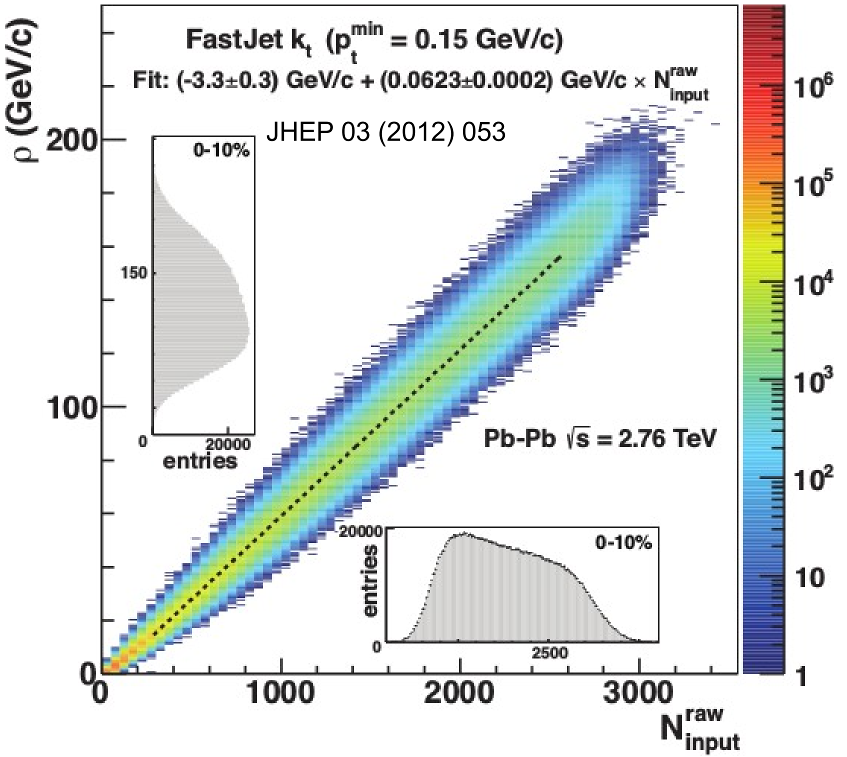


Jets in A+A collisions: Dealing with background

Focus on smaller angles

- Pros
  - Background is smaller
  - Background fluctuations smaller
- Cons:
  - Modifications expected at higher R
  - Biases sample towards quarks

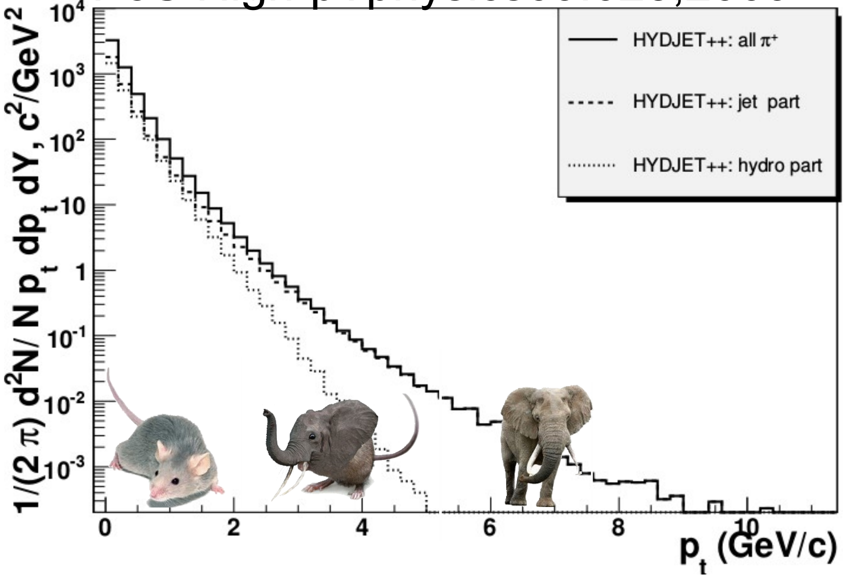
Aside: "quark" and "gluon" jet only defined at leading order.



Focus on high p_T

- Pros:
  - Reduces combinatorial background
- Cons:
  - Cuts signal where we expect modifications
  - Could bias towards partons which have not interacted
  - Biases sample towards quark jets

PoS High-pTphysics09:023,2009

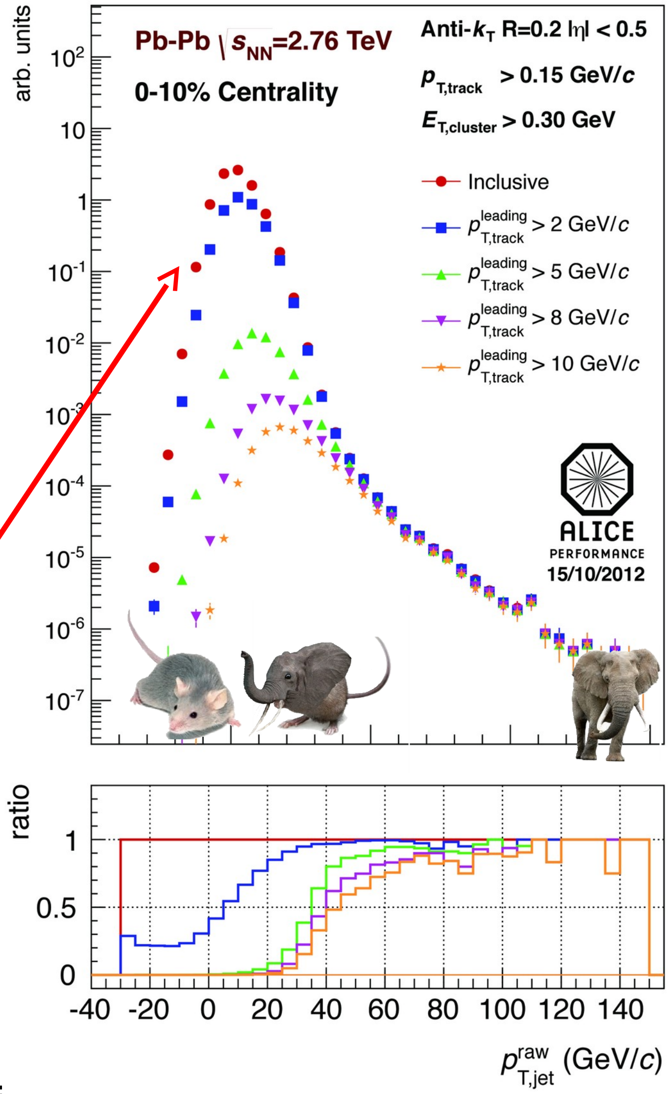


"Quark" and "gluon" jets only defined at leading order!

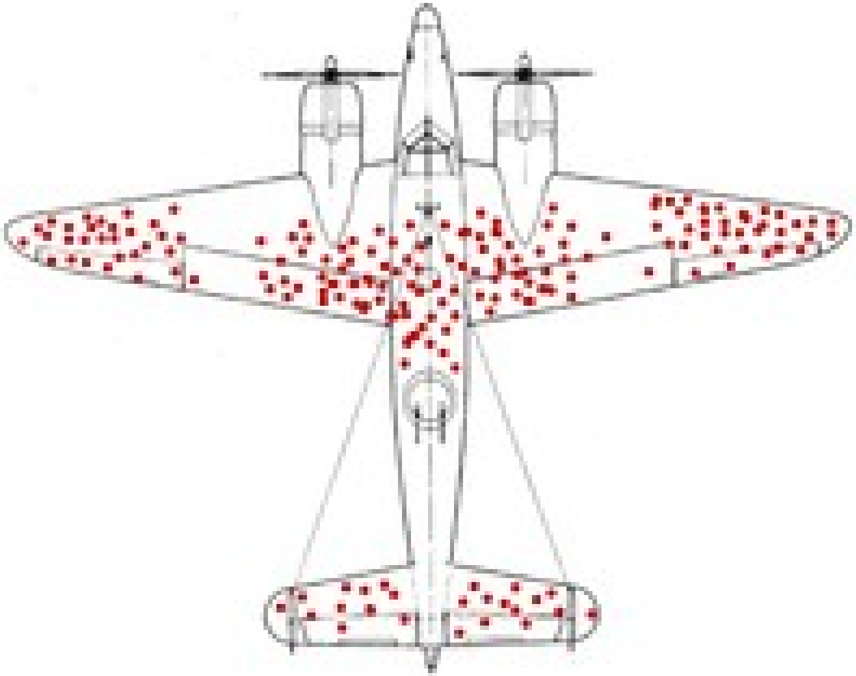
Area-based subtraction

- ALICE/STAR
- Require leading track p_T > 5 GeV/c
  - Suppresses combinatorial "jets"
  - Biases fragmentation
- No threshold on constituents
- Limited to small R

Combinatorial "jets"



Survivor bias



- WWII Example: holes planes returning indicate where it's *safer* to get hit
- We're looking at the jets which *remain*

http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/

http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/


What you see depends on what you're looking for
http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/

Bias & background

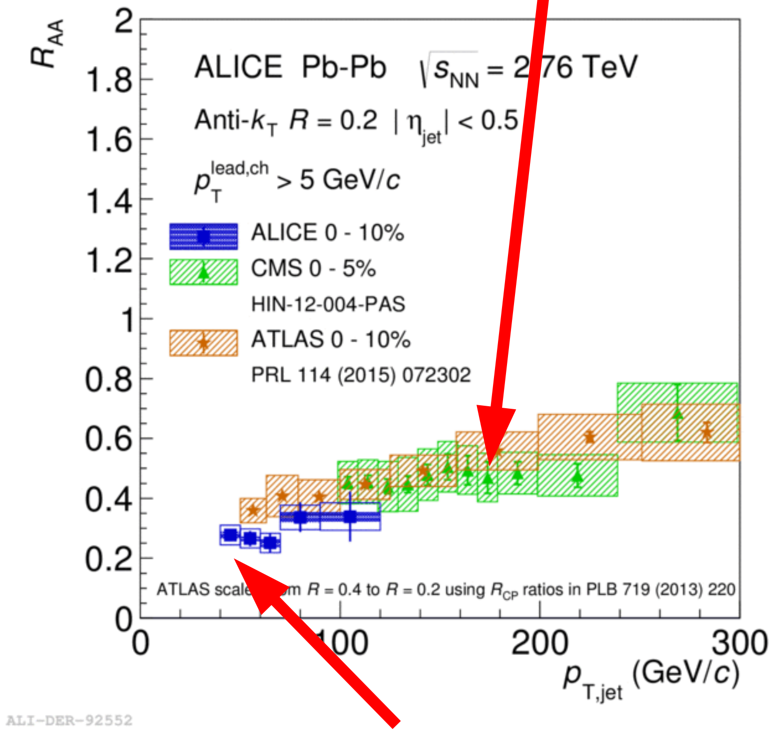
- **Experimental background subtraction methods:** complex, make assumptions, apply biases
- **Survivor bias:** Modified jets probably look more like the medium
- **Quark/Gluon bias:**
  - Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996),]
  - Gluon jets reconstructed with k_T algorithm have more particles than jets reconstructed with anti-k_T algorithm [Phys. Rev. D 45, 1448 (1992)]
  - Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]
- **Fragmentation bias:** Experimental measurements explicitly select jets with hard fragments

http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/

Iterative procedure

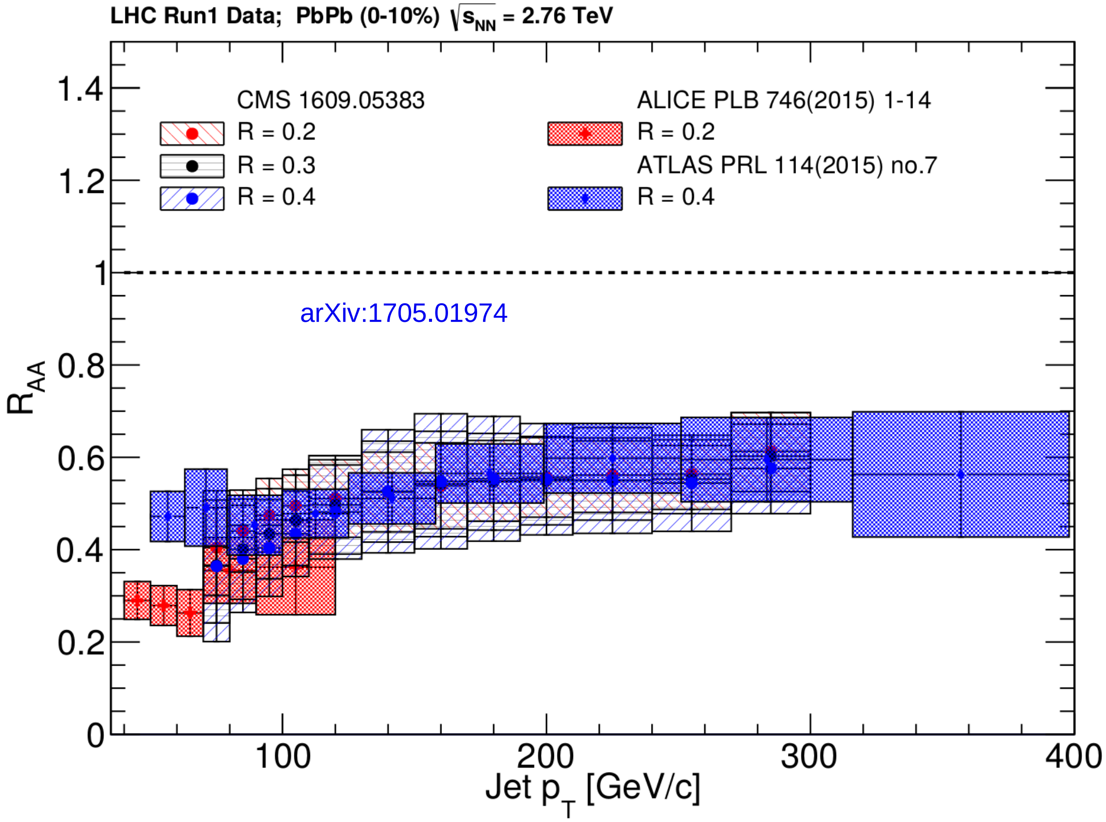
- Used by ATLAS & CMS
- ATLAS
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with
    $E_{tower} > \langle E_{tower} \rangle$
    Track jets: Use tracks with p_T>4 GeV/c
  - Calorimeter jets from above with E>25 GeV and track jets with p_T>10 GeV/c used to estimate background again.
  - Calorimeter tracks matching one track with p_T>7 GeV/c or containing a high energy cluster E >7 GeV are used for analysis down to E_{jet} = 20 GeV

Constituent biases don't matter that much up here

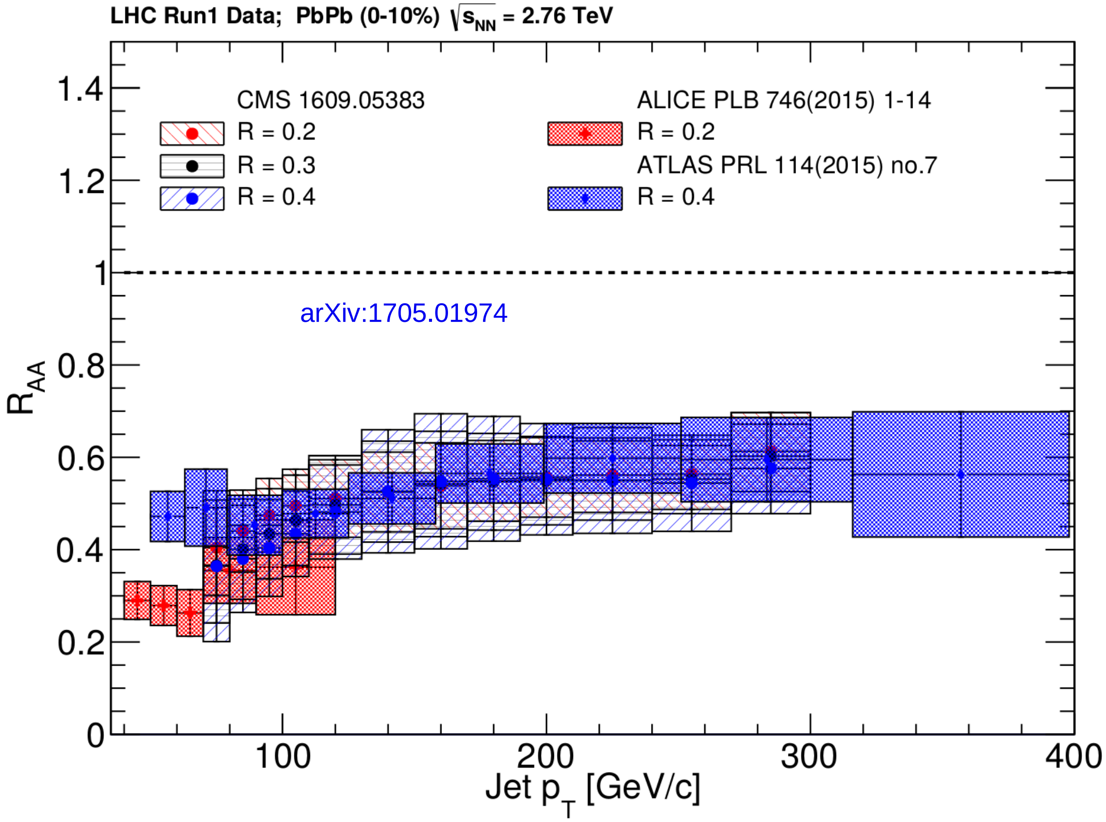


But they do matter down here!

Jet R_{AA}


LHC Run1 Data; PbPb (0-10%) $\sqrt{s_{NN}}$ = 2.76 TeV
CMS 1609.05383
R = 0.2
R = 0.3
R = 0.4
ALICE PLB 746(2015) 1-14
R = 0.2
ATLAS PRL 114(2015) no.7
R = 0.4
arXiv:1705.01974
R_{AA}
Jet p_T [GeV/c]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
100
200
300
400

Jet R_{AA}



Tension between ATLAS & ALICE/CMS

ATLAS

Background subtraction method:

- Iterative procedure
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with
    $E_{tower} > \langle E_{tower} \rangle$
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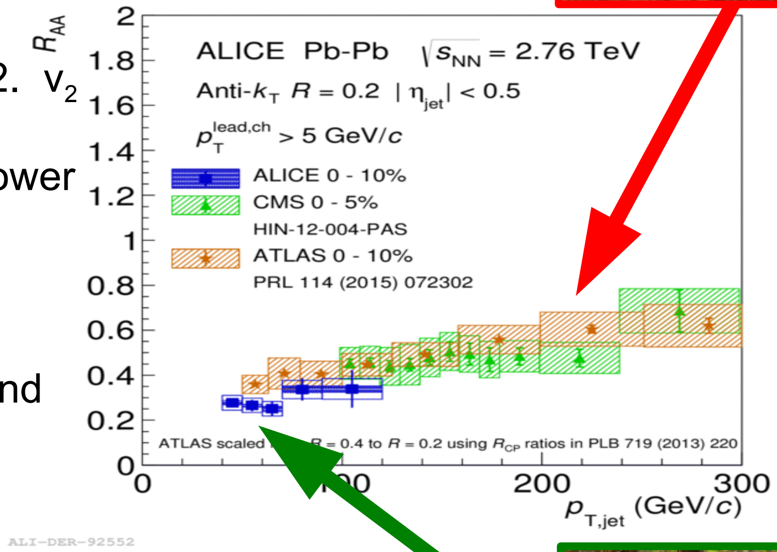
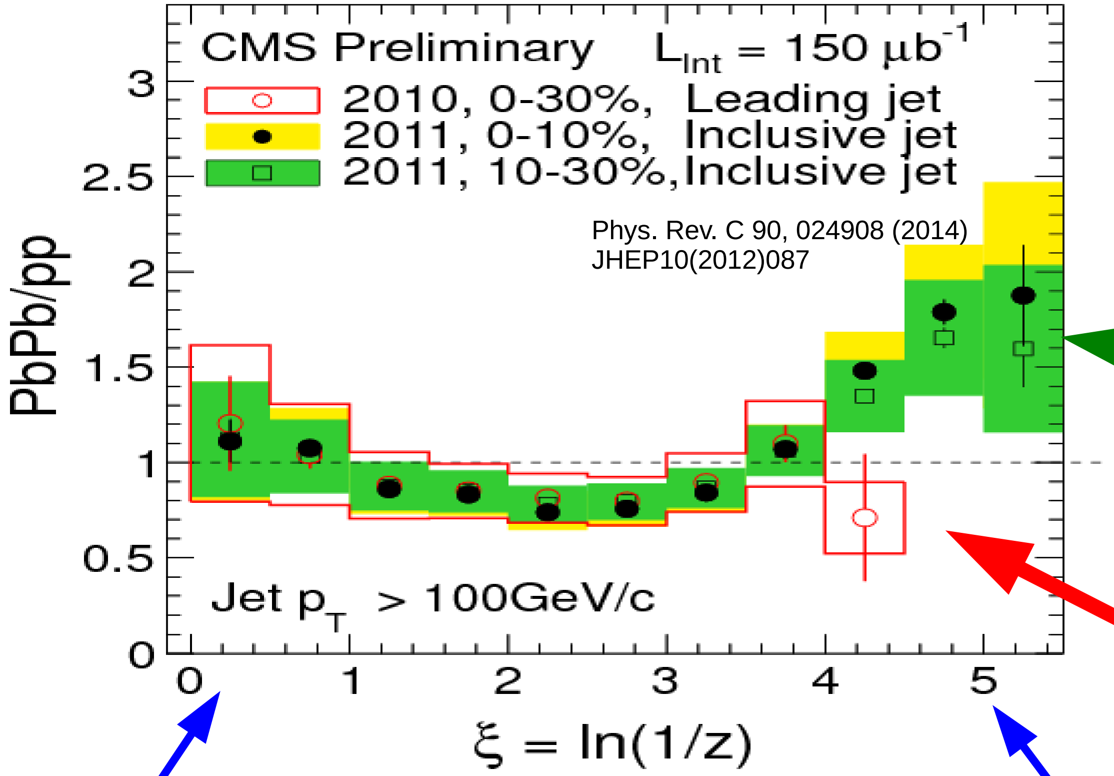


Constituent biases don't matter that much up here

But they do matter down here!

Phys. Lett. B 719 (2013) 220-241

What you see depends on where you look



High p_T

$z = p_T/E_{jet}$

Low p_T

Mini-summary

- Most studies do one or more of the following:
  - Explicitly apply a (non-purturbative) bias
  - *Implicitly* apply a (non-purturbative) bias
  - Focus on small R
  - Focus on high pT
- May also → survivor bias
- Background subtraction should be part of definition of algorithm

What are the dominant uncertainties?

Analysis steps

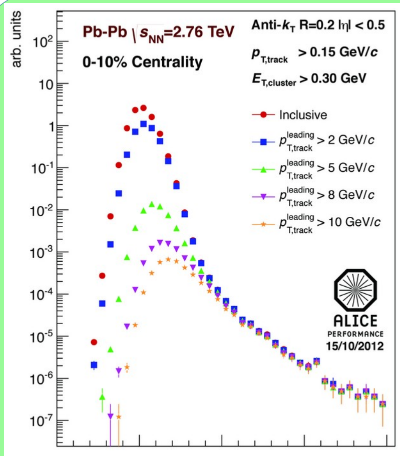
Tracks

Clusters

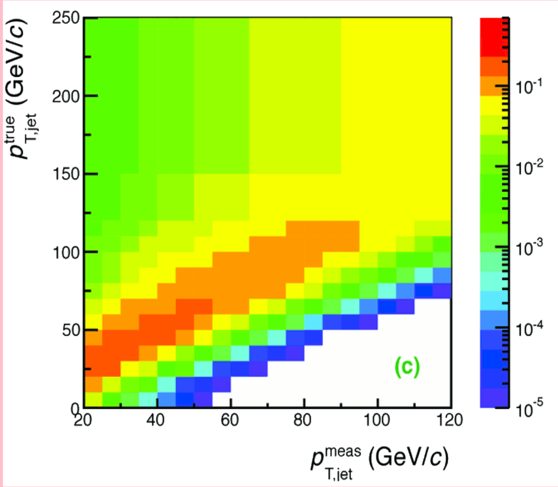
Jet finding algorithm

Jet candidates

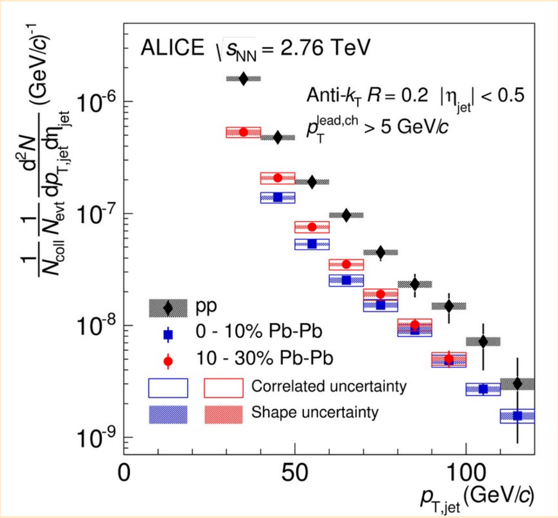
Background subtraction



Jet spectrum smeared by energy resolution, background fluctuations



Unfolding – corrects for single track reco ε, E resolution, background fluctuations



Corrected spectra

Unfolding

$$\vec{v} = R\vec{\mu} + \vec{\beta}$$

$$v_i = \sum_{j=1}^{M} (R_{ij}\mu_j) + \beta_i$$

- $\vec{\mu}$: the “true” histogram
- $\vec{v}$: the actual data we measure
- $\vec{\beta}$: background
- R : the response matrix

Simple Solution (Inversion)

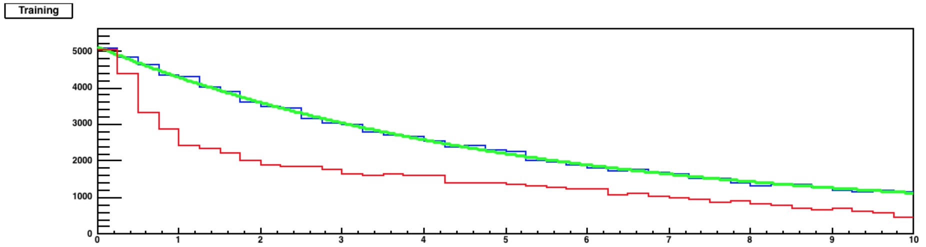
- Rearrange $\vec{v} = R\vec{\mu} + \vec{\beta}$ to get $\vec{\mu} = R^{-1}(\vec{v} - \vec{\beta})$
- Problem: we don't have $\vec{v}$, we have $\vec{n}$, the measured data, which is subject to statistical fluxuations.
- We assume n_i is the maximum likelihood estimator for v_i, then solve for the estimator $\hat{\mu} = R^{-1}(\vec{n} - \vec{\beta})$.
- R^{-1} is obtained from R through simple matrix inversion

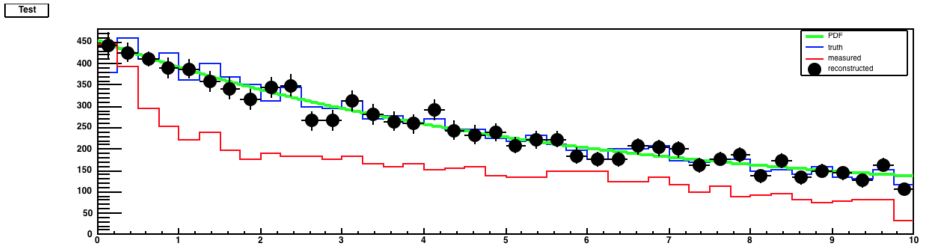
Iterative Bayesian Method

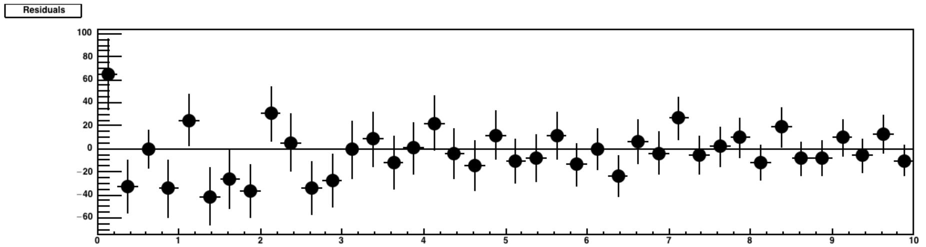
- Using prior knowledge, start with an initial guess for the distribution of true histograms $P^0\,(\hat{\mu})$
- Use Bayes' Theorem to invert the response matrix $P\left(\hat{\mu}_i|v_j^{sig}\right) = \frac{P\left(v_j^{sig}|\hat{\mu}_i\right)P^0\,(\hat{\mu}_i)}{\sum_{l=1}^{M} P\left(v_j^{sig}|\hat{\mu}_l\right)P^0\,(\hat{\mu}_l)}$
- $\hat{\mu}_i = \frac{1}{\epsilon_i}\sum_{j=1}^{N} v_j^{sig}\, P\left(\hat{\mu}_i|v_j^{sig}\right)$ where ϵ_i is the detector efficiency
- Plug in the newly obtained $P\left(\hat{\mu}_i|v_j^{sig}\right)$ and $\hat{\mu}_i$ as new priors, then repeat
- Terminate before the wildly oscillating true inverse is reached (usually ~4 iterations) to preserve some smoothness

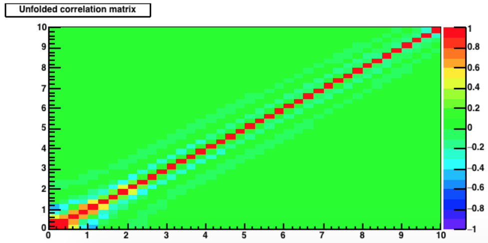
RooUnfold-Bayes

- RooUnfoldTest.cxx
- method = Bayes
- Exponential training and testing





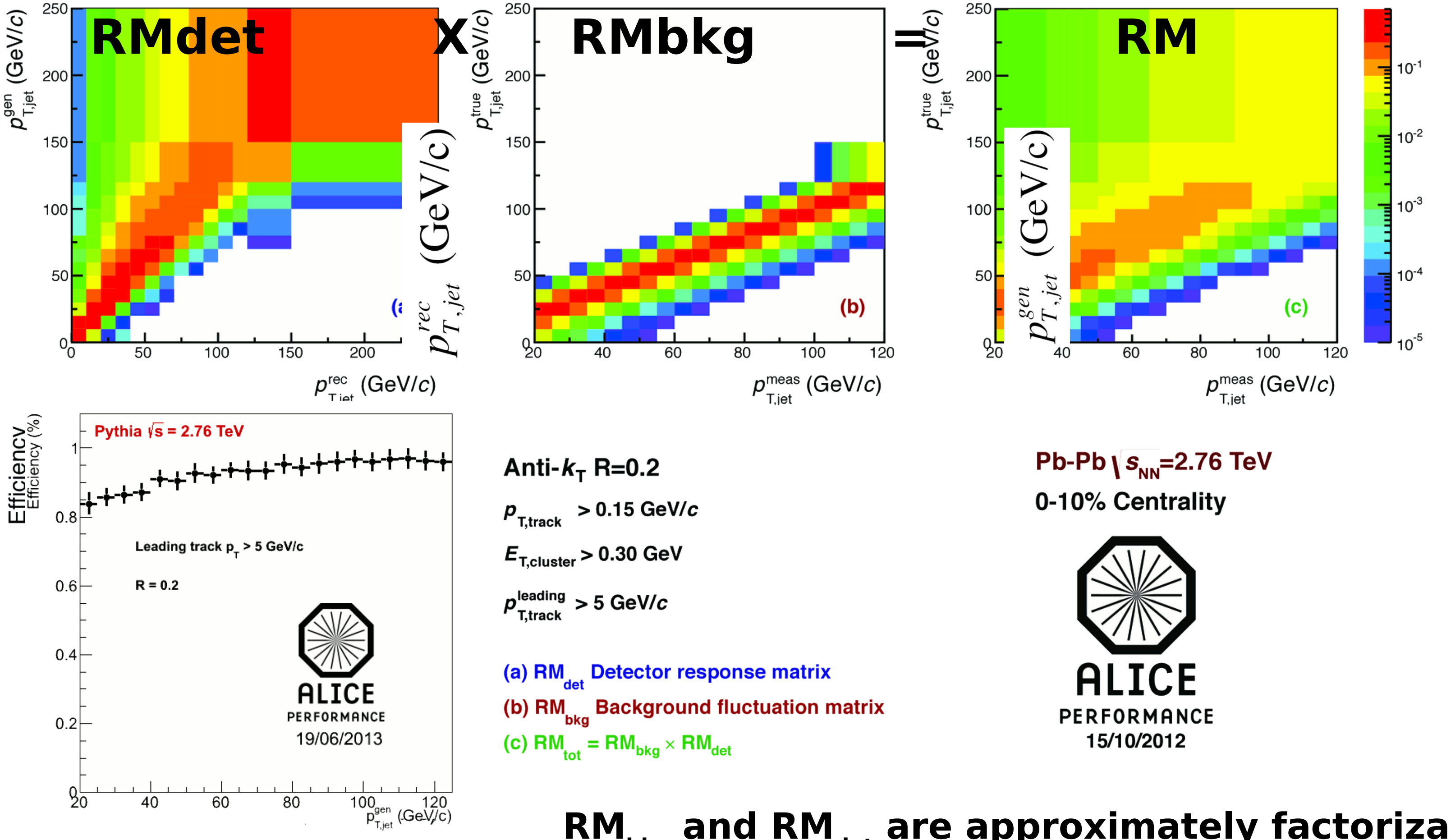




About unfolding...

- d'Agostini (author of Bayesian unfolding algorithm) says you should avoid it if you can
- Necessary when experimental resolution is poor
  - Ex: Single particle spectra $\frac{\sigma_p}{p} \ll w_{bin} \rightarrow$ unfolding unnecessary
  - Ex: Jet spectra $\frac{\sigma_p}{p} \approx w_{bin} \rightarrow$ unfolding necessary
- Algorithm assumes response matrix is correct
  - Matching reconstructed and simulated jets is non-trivial!
- Corrects for multiple experimental effects simultaneously
  - Difficult to disentangle different effects
  - Leads to non-trivial uncertainty correlations between data points due to algorithm
  - May not handle systematic correlations between effects correctly

Jets in ALICE: Response Matrix Construction



Anti-k_T R=0.2

$p_{T,track}$ > 0.15 GeV/c

$E_{T,cluster}$ > 0.30 GeV

$p^{leading}_{T,track}$ > 5 GeV/c

(a) RM_{det} Detector response matrix

(b) RM_{bkg} Background fluctuation matrix

(c) $RM_{tot} = RM_{bkg} \times RM_{det}$

Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

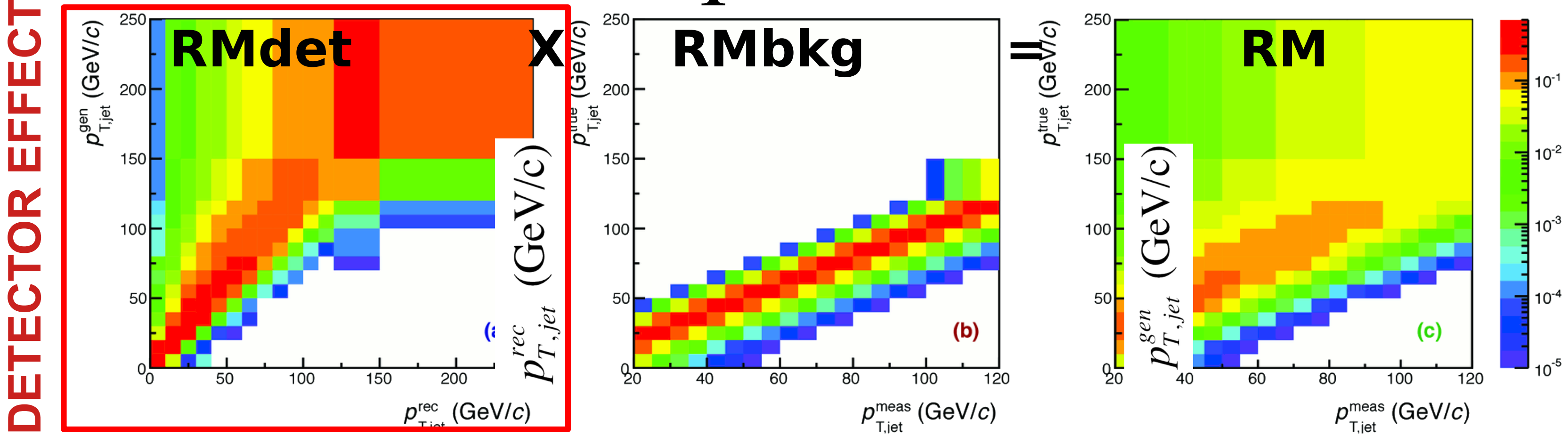
0-10% Centrality

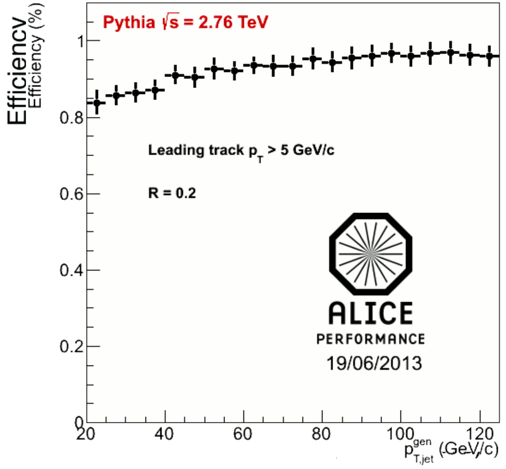
ALICE PERFORMANCE

15/10/2012

RM_{bkg} and RM_{det} are approximately factorizable

Jets in ALICE: Response Matrix Construction





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ALI-PERF-44520

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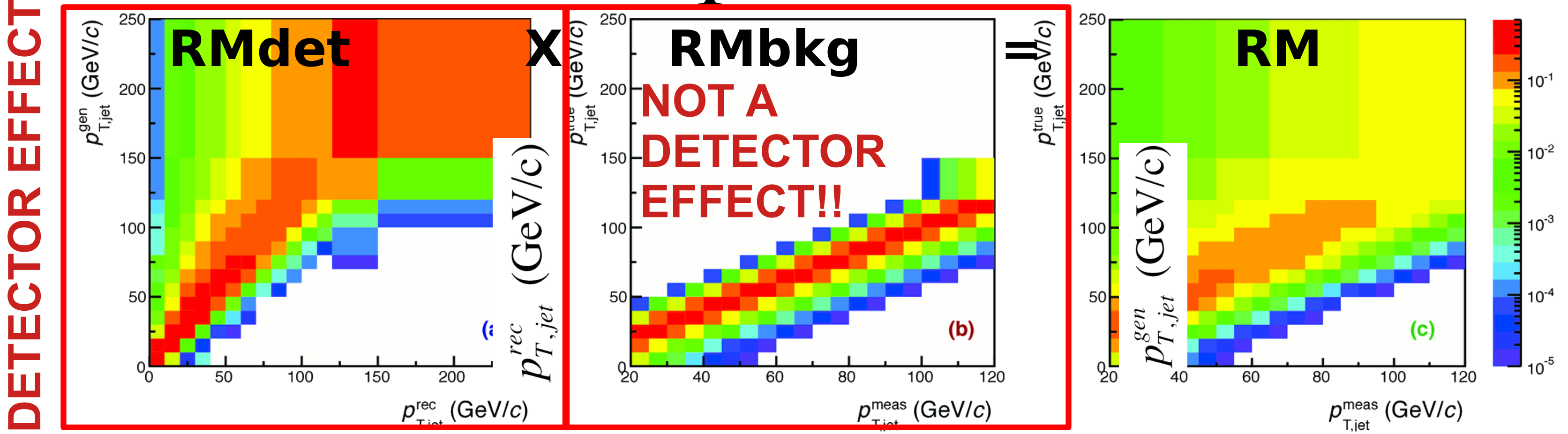

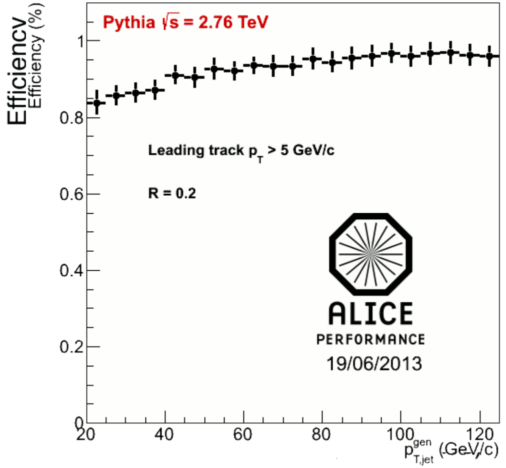

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ALICE PERFORMANCE

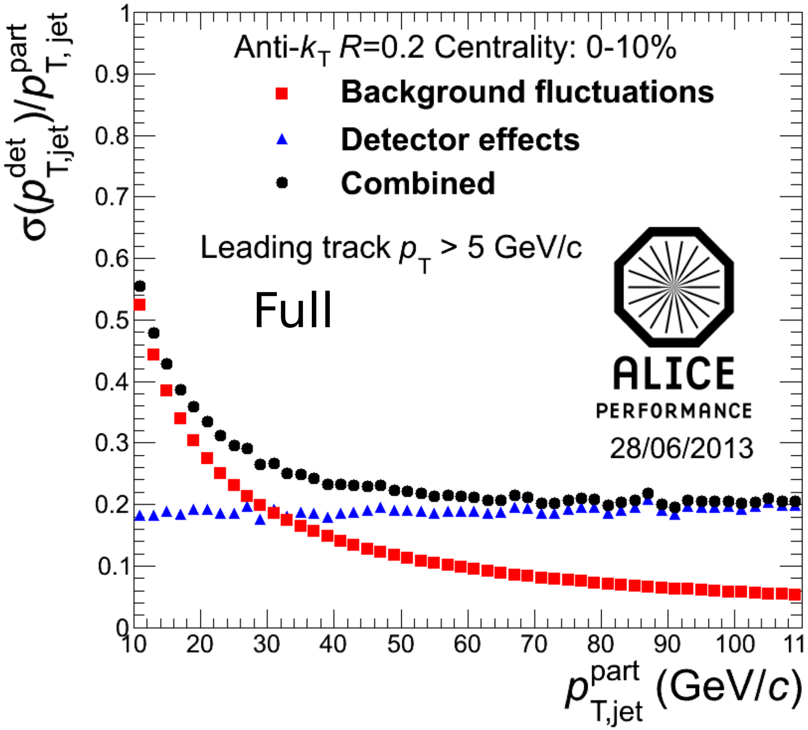
15/10/2012

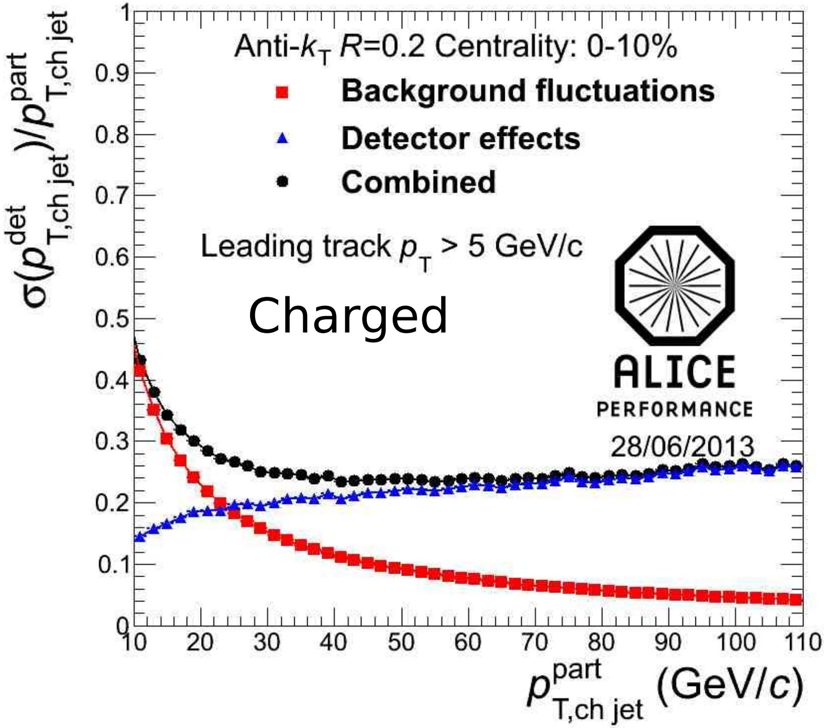
RM_{bkg} and RM_{det} are approximately factorizable

Response matrix includes assumptions about

- Detector response
  - Including particle composition of jets!
- Fragmentation and hadronization
  - How does hadronization influence the width of your jet?
- Background and/or background fluctuations
- How you match reconstructed (“detector level”) and true (“particle level”) jets

Jet Momentum Resolution





- Jet resolution
  - Dominated by background fluctuations at low momentum
  - Dominated by detector effects at high momentum

Mini-summary

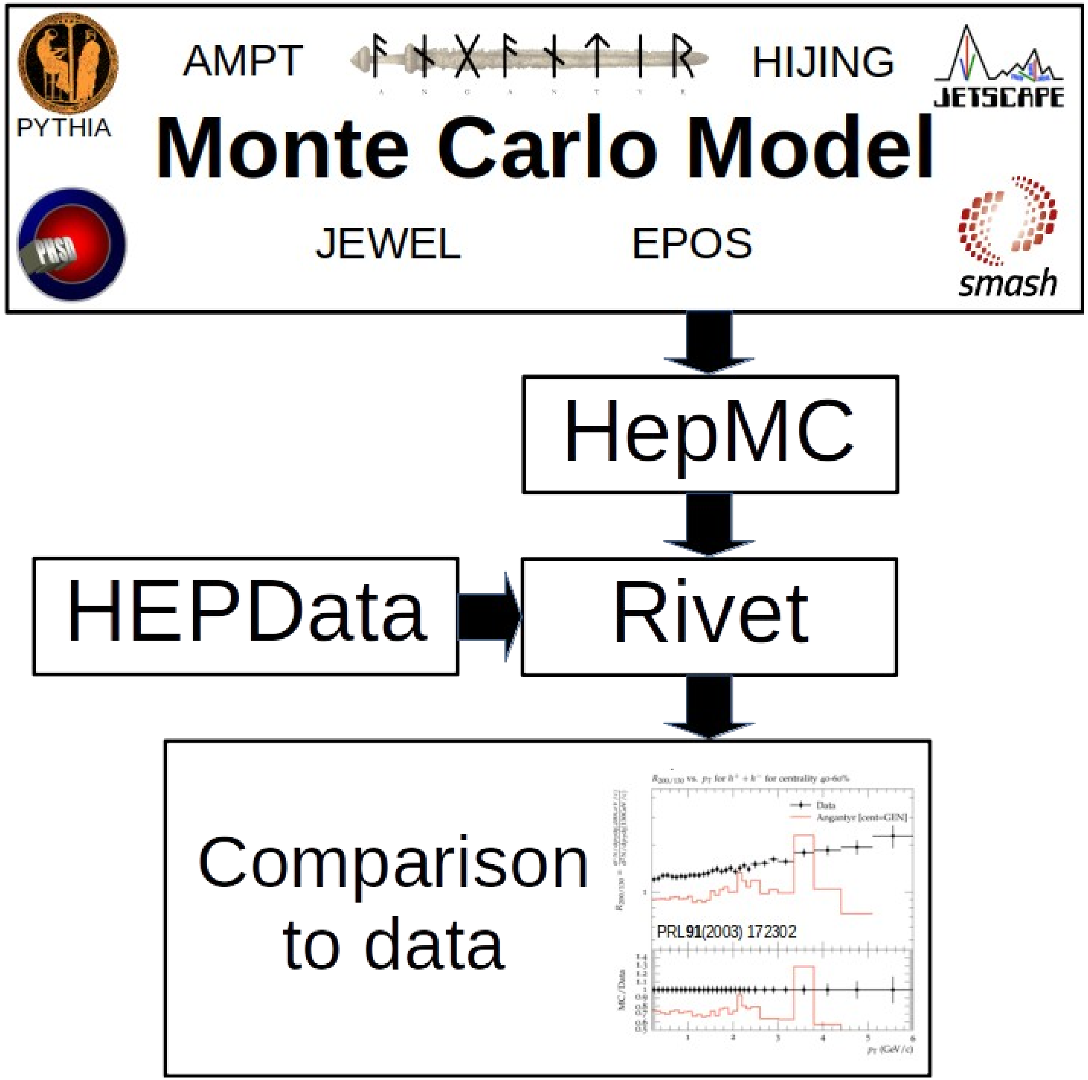
- Jet energy resolution is fundamentally large
  - Measuring multiple correlated particles!
  - Be skeptical of jet measurements with <10% uncertainties
- Unfolding is complicated, often unstable, and hard
- Construction of response matrix includes several assumptions

Jets in A+A collisions: How to compare to models

Snowmass Accord: Apply the same algorithm to data and your model. Then the measurement and the calculation are the same.

Rivet: Apply the same algorithm to data and your model. Then the measurement and the calculation are the same.

What is Rivet?


AMPT
HIJING
PYTHIA
JETSCAPE
Monte Carlo Model
JEWEL
EPOS
PHSD
smash
HepMC
HEPData
Rivet
Comparison to data
Data
Angantyr [cent=GEN]
PRL 91(2003) 172302
MC / Data

Why use Rivet?

- Facilitates comparisons between Monte Carlos and data
- It’s not that hard
- It preserves analysis details

Rivetizing Heavy Ion Collisions at RHIC 2020

November 30, 2020 to December 4, 2020
Online
US/Eastern timezone

- Overview
- Remote connection
- Announcement
- Registration
- Participant List
- Organizing Committee
- Code of Conduct
- HEPData@RHIC

Support

christine.nattrass@utk.edu

antonio.silva@cern.ch

Workshop to implement RHIC analyses in Rivet

Starts Nov 30, 2020, 9:00 AM
Ends Dec 4, 2020, 12:00 PM
US/Eastern

Online

Antonio Carlos Oliveira da Silva
Christine Nattrass

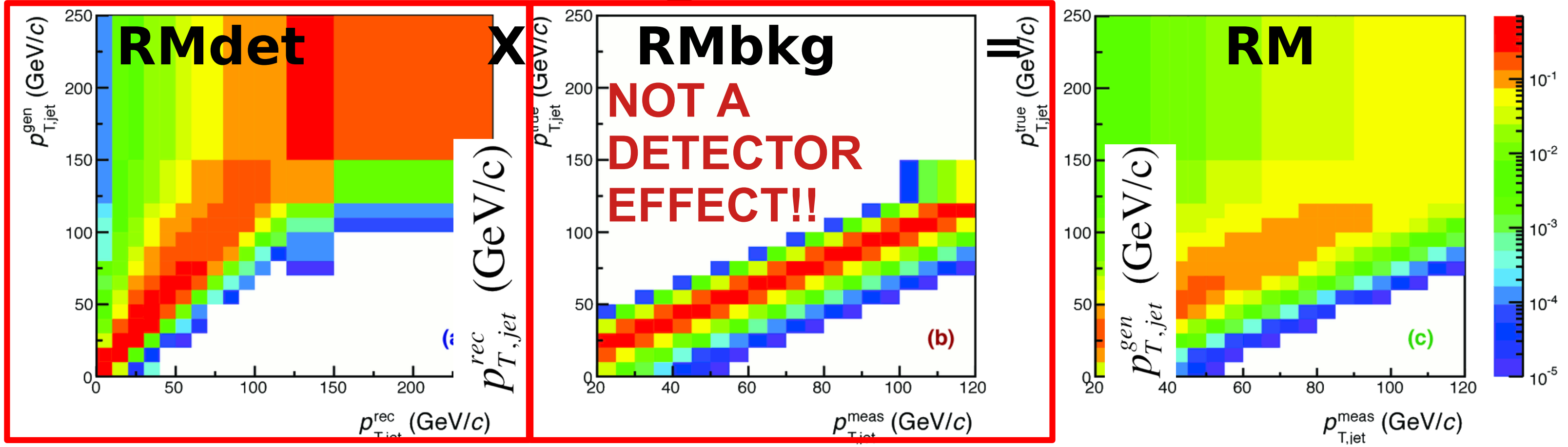
There are no materials yet.

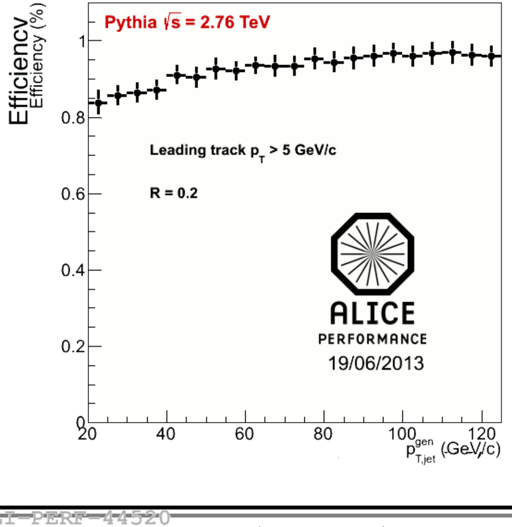
Registration
Registration for this event is currently open.

Register now

Jets in ALICE: Response Matrix Construction

DETECTOR EFFECT





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Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

0-10% Centrality

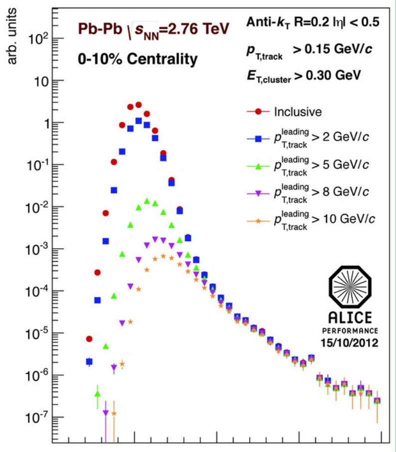
ALICE PERFORMANCE

15/10/2012

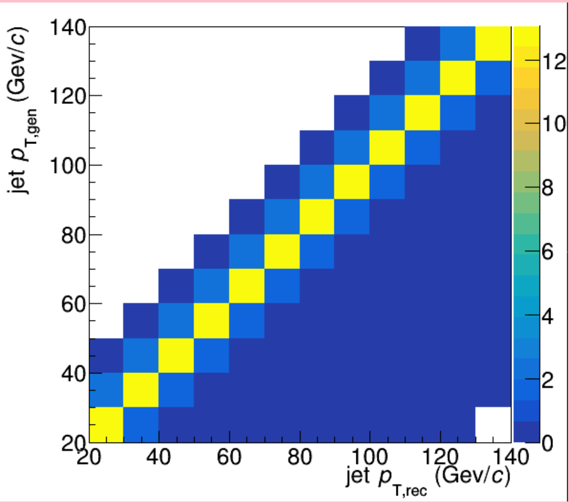
RM_{bkg} and RM_{det} are approximately factorizable

Analysis steps: Full Monte Carlo

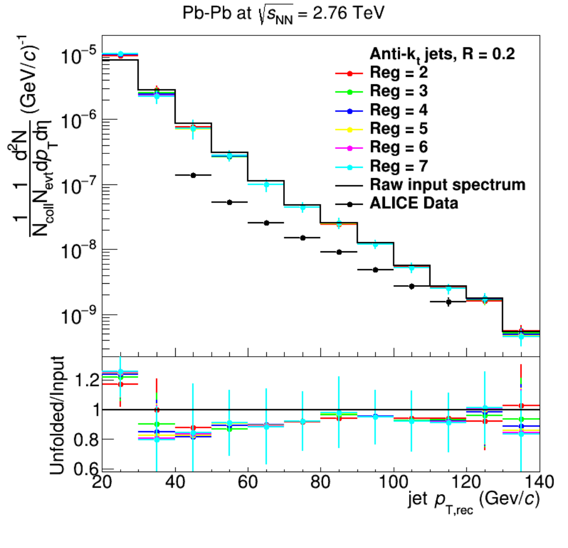
Particles → Jet finding algorithm → Jet candidates → Background subtraction



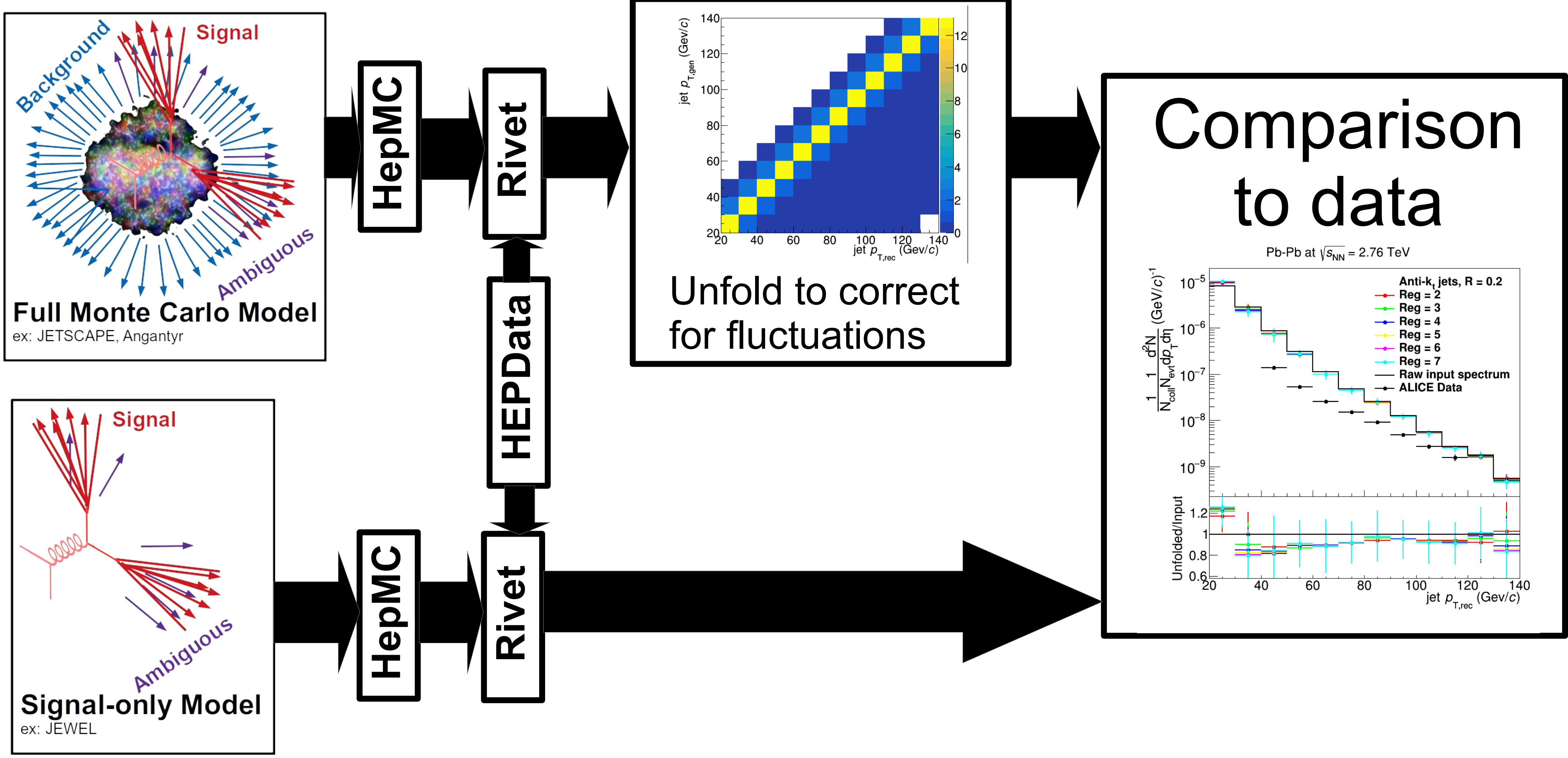
Jet spectrum smeared by energy resolution



Unfolding – ***corrects for background fluctuations***



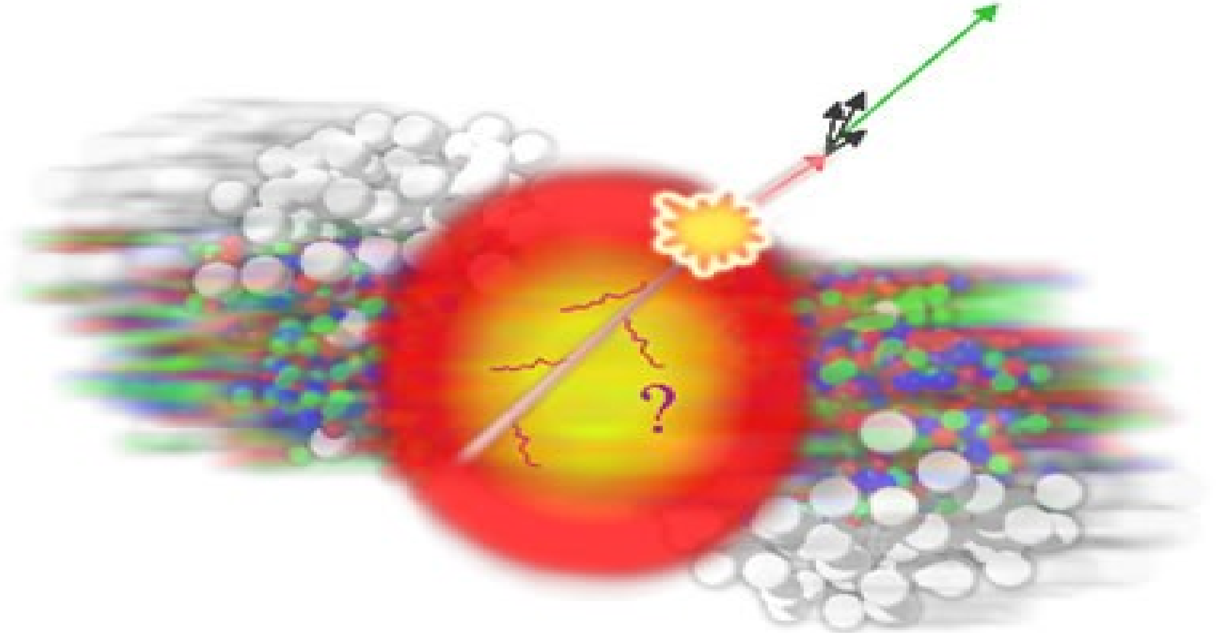
Corrected spectra


Background
Signal
Ambiguous
Full Monte Carlo Model
ex: JETSCAPE, Angantyr
HepMC
Rivet
HEPData
Unfold to correct for fluctuations
jet $p_{T,gen}$ (Gev/c)
jet $p_{T,rec}$ (Gev/c)
Comparison to data
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
Anti-k_t jets, R = 0.2
Reg = 2
Reg = 3
Reg = 4
Reg = 5
Reg = 6
Reg = 7
Raw input spectrum
ALICE Data
$\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{d^2N}{dp_T d\eta}$ (GeV/c)$^{-1}$
Unfolded/Input
Signal
Ambiguous
Signal-only Model
ex: JEWEL

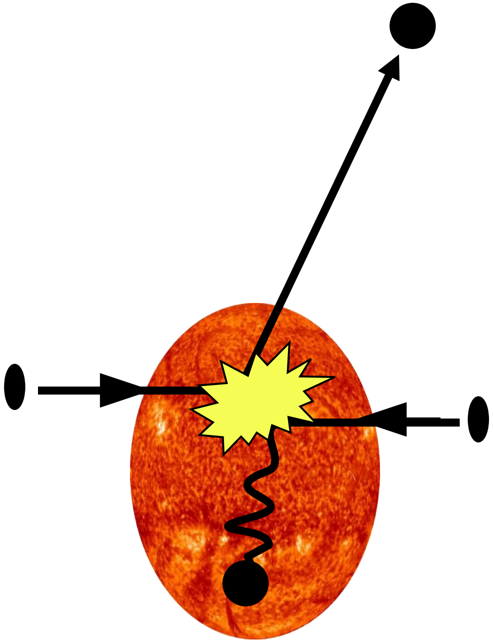
Mini-summary

- Experimental techniques can bias measurement in subtle ways
  - Background subtraction
  - Kinematic cuts
  - Choice of jet finder, R
  - Centrality determination
  - Technique for finding reaction plane
- Unclear how these influence the measurement
- Safest to do the same analysis on data and model
  - But unfolding is necessary in a full Monte Carlo model!

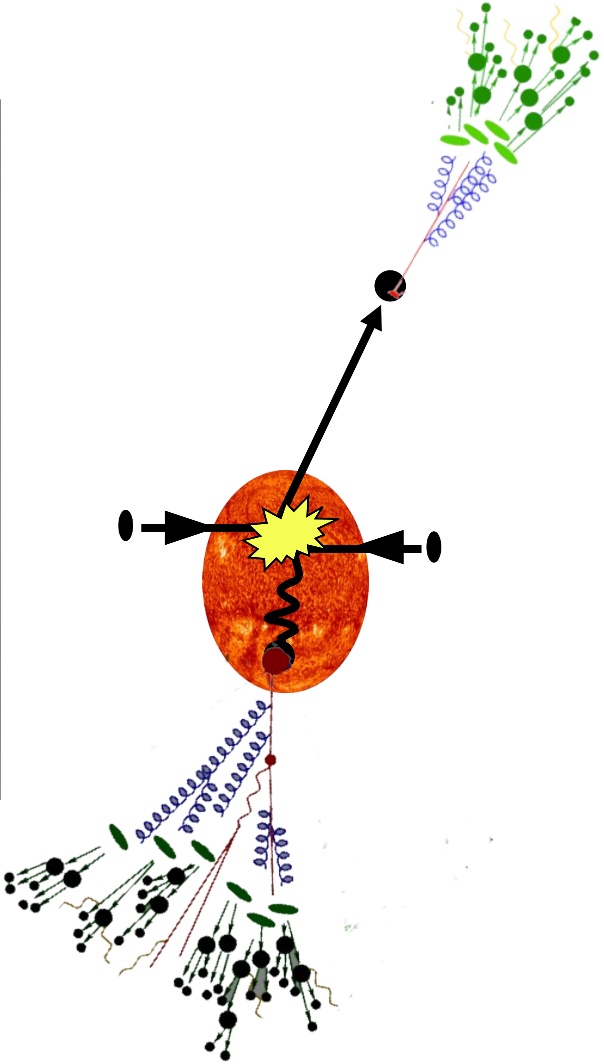
A skeptic’s guide to jets
Part 2: Where we are going



Christine Nattrass
University of Tennessee, Knoxville



There is no partionic energy loss.



There is only partionic energy redistribution.

What is jet (sub)structure?

A Whatever I am measuring!

B Any new jet observable

C Any observable which measures the structure of jets.

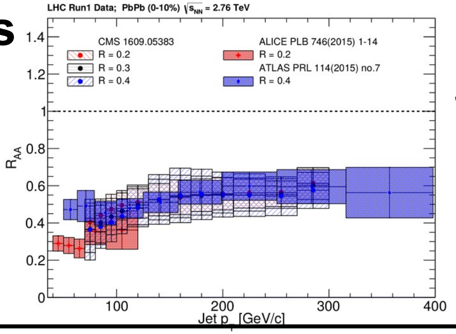
D A cool buzzword

E I don’t know but it sounds cool and gets me talks/grants

Types of observables

I. Minimally sensitive to structure

Observables
- (Jet) R_{AA}
- A_j
- I_{AA}
- (Jet) v_2

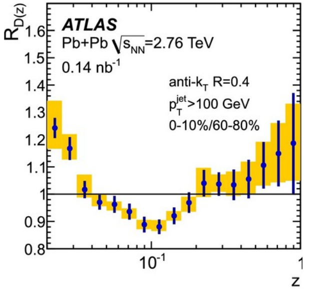


Jet properties:
- E

Jets not required

II. Sensitive to <structure> of <jets>

Observables
- Fragmentation functions
- Jet shapes
- Correlations
- ...



Jet properties:
- E
- Const. p_T, φ, η

Higher precision

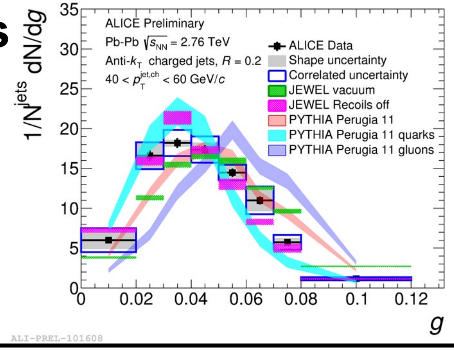
Average background subtraction OK

Higher/different sensitivity?

Need new background subtraction technique

III. Sensitive to distribution of structures

Observables
- Girth
- Dispersion
- p_TD
- Jet mass
- ...

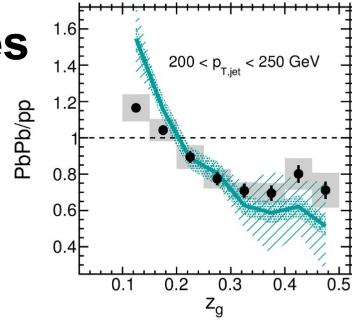


Jet properties:
- E
- Const. p_T, φ, η

Jets required

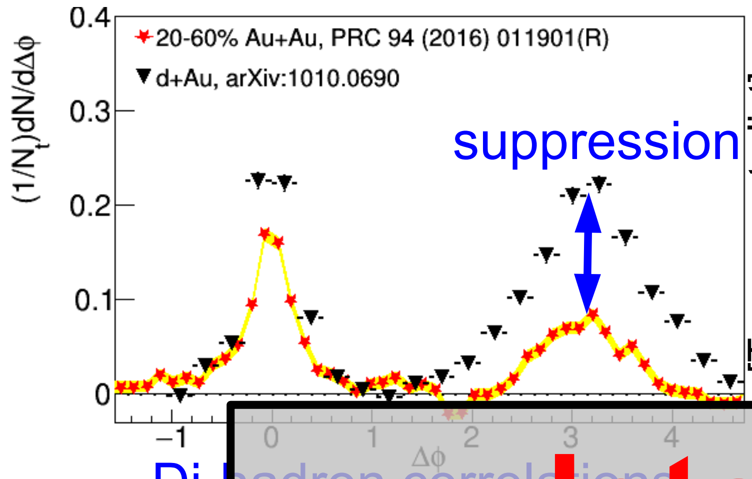
IV. Sensitive to parton shower structure

Observables
- Grooming
- $N_{\text{subjettiness}}$
- ...



Jet properties:
- E
- Const. p_T, φ, η
- Multi-const. correlations

Type I: Energy loss



Di-hadron correlations

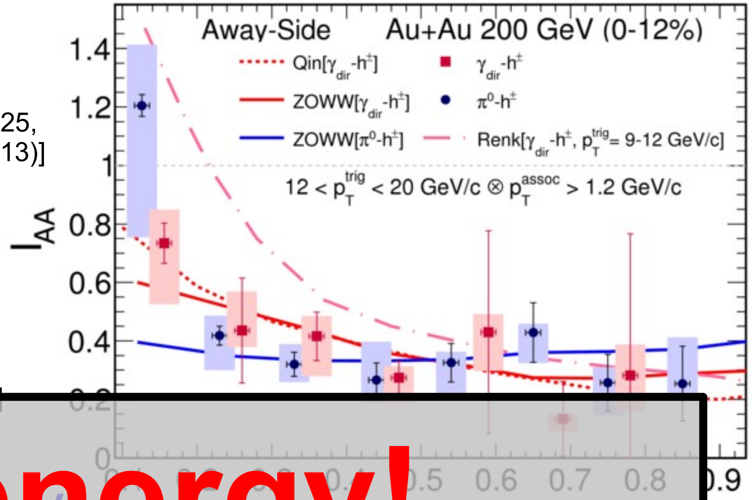
[Too many to list]

Jet v_2

[Phys.Lett. B 753 (2016) 511-525, Phys. Rev. Lett.111 152301 (2013)]

γ-jet correlations

[Phys. Lett. B 718 (2013) 773]



suppression

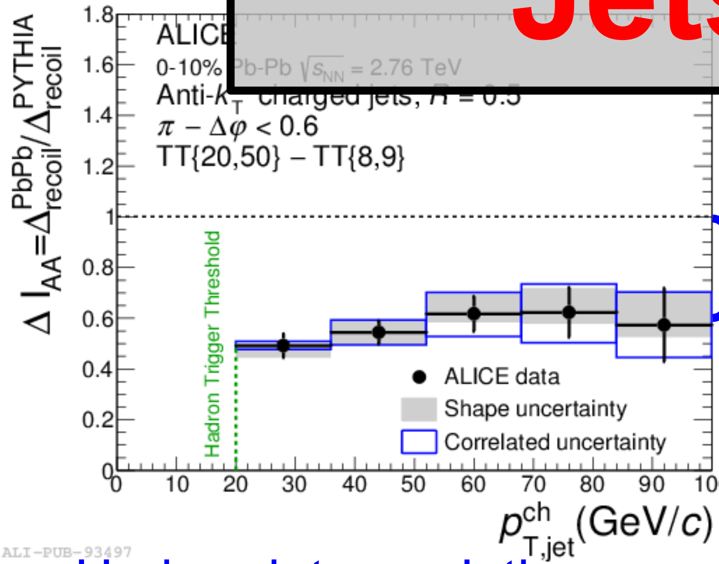
[Phys.Rev.C80:024908,2009, Phys.Rev.D82:072001,2010, Phys.Rev.C82:034909,2010, Physics Letters B 760 (2016)]

High-p_T hadron v_2

[too many to list]

γ-hadron correlations

Jets lose energy!



suppression

[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

Hadron-jet correlations

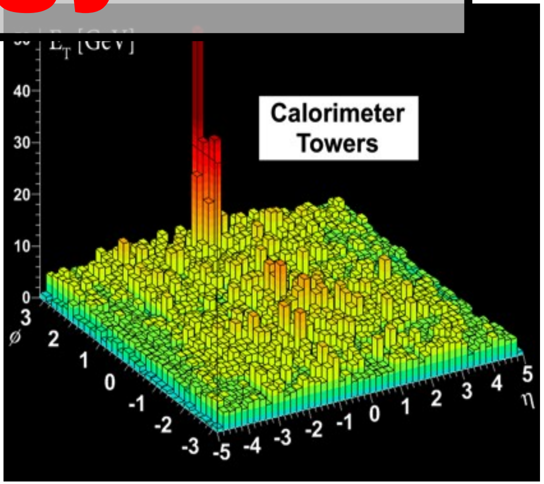
Au+Au $\sqrt{s_{NN}}$=200 GeV

$$\hat{q} = 1.2 \pm 0.3 \quad GeV^2$$

Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV

$$\hat{q} = 1.9 \pm 0.7 \quad GeV^2$$

[Phys. Rev. C 90, 014909 (2014)]

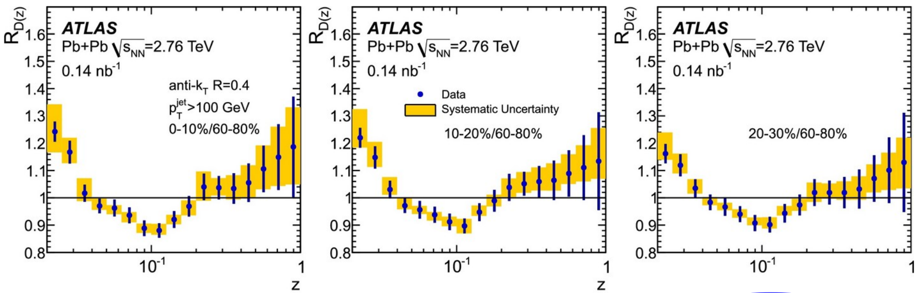


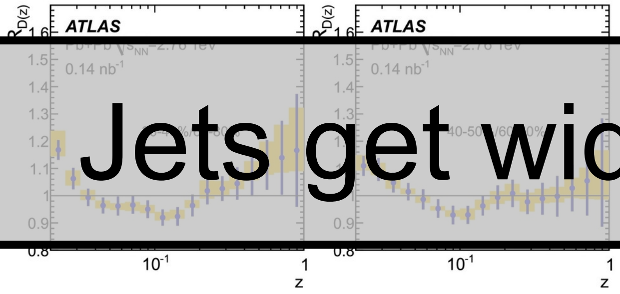
Dijet asymmetry

[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

Type II: Fragmentation

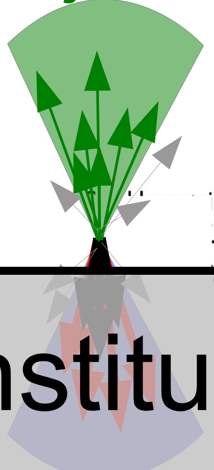
Fragmentation functions with jets





$z=p_T/E_\gamma$

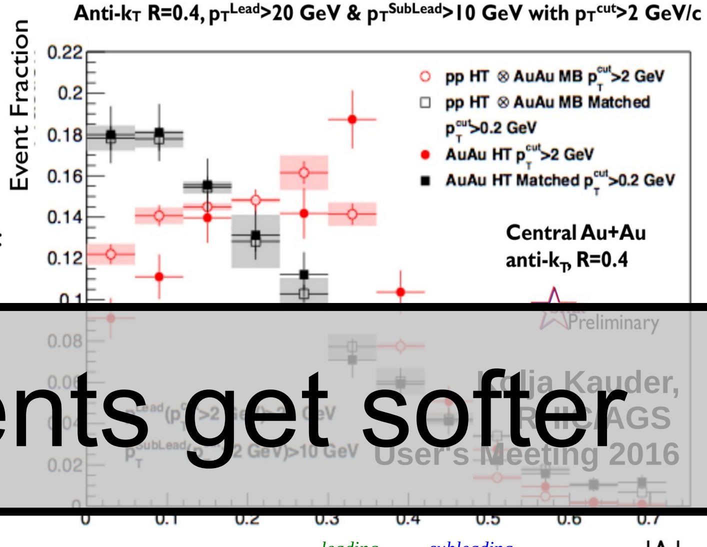
Leading jet



Subleading jet

Di-jet asymmetry

arXiv:1609.03878



$$A_j=\frac{p_T^{leading}-p_T^{subleading}}{p_T^{leading}+p_T^{subleading}}$$

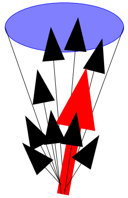
Jets get wider and constituents get softer

Di-hadron correlations

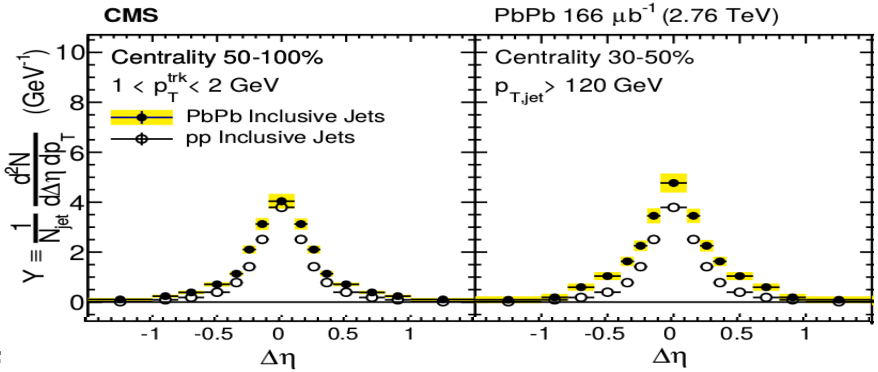
[Lots of papers]

Jet shapes

[arXiv:1708.09429, arXiv:1512.07882, arXiv:1704.03046]

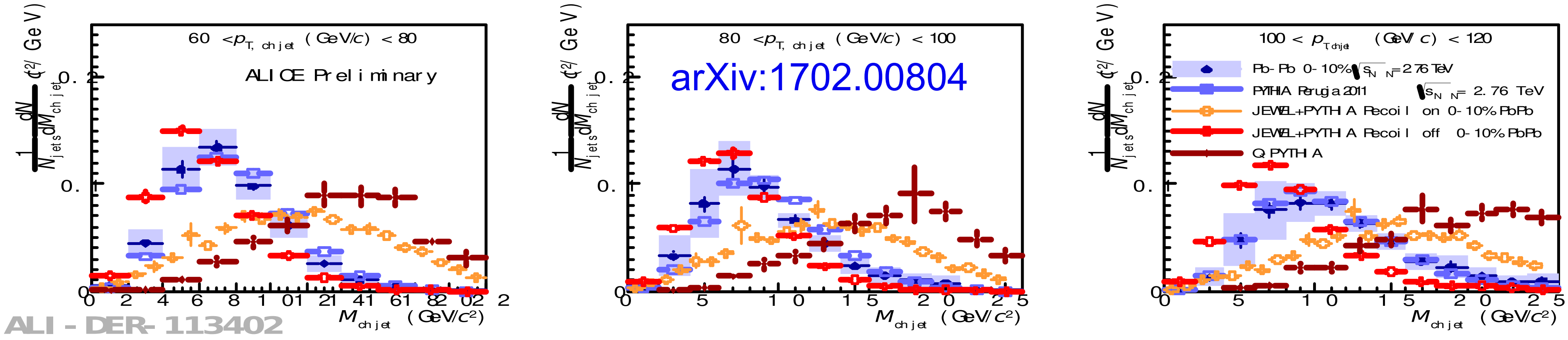


Jet-hadron correlations



Type III: Distribution of properties

Jet mass

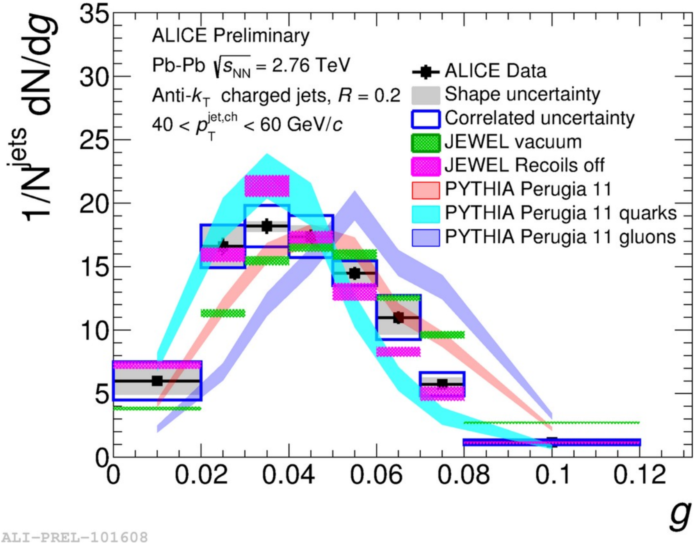


$$M = \sqrt{p^2 - p_T^2 - p_z^2}$$

$$p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i . \quad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i$$

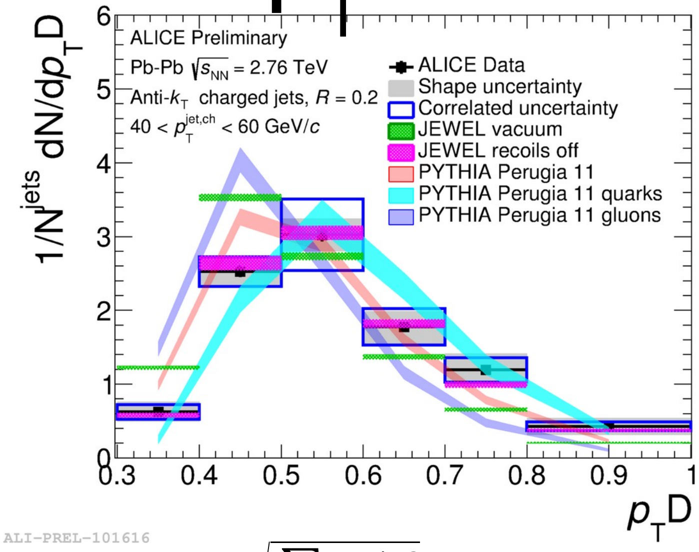
- Quenching models (JEWEL, Q-PYTHIA) show a larger mass than pp-like PYTHIA jets
- Pb-Pb measurement can discriminate among these predictions

Girth g



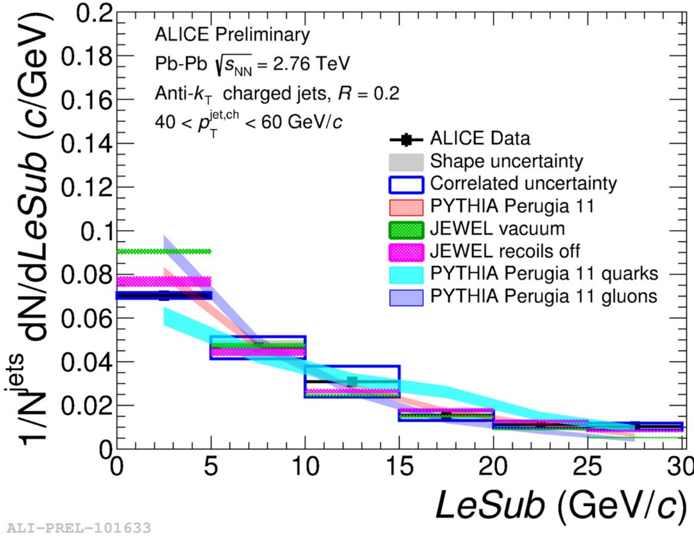
$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} r_i$$

Dispersion $p_T D$



$$p_T D = \frac{\sqrt{\sum_{i \in jet} (p_T^i)^2}}{\sum_{i \in jet} p_T^i}$$

LeSub



$$LeSub = p_T^{leading} - p_T^{subleading}$$

Jets are slightly more collimated than in pp

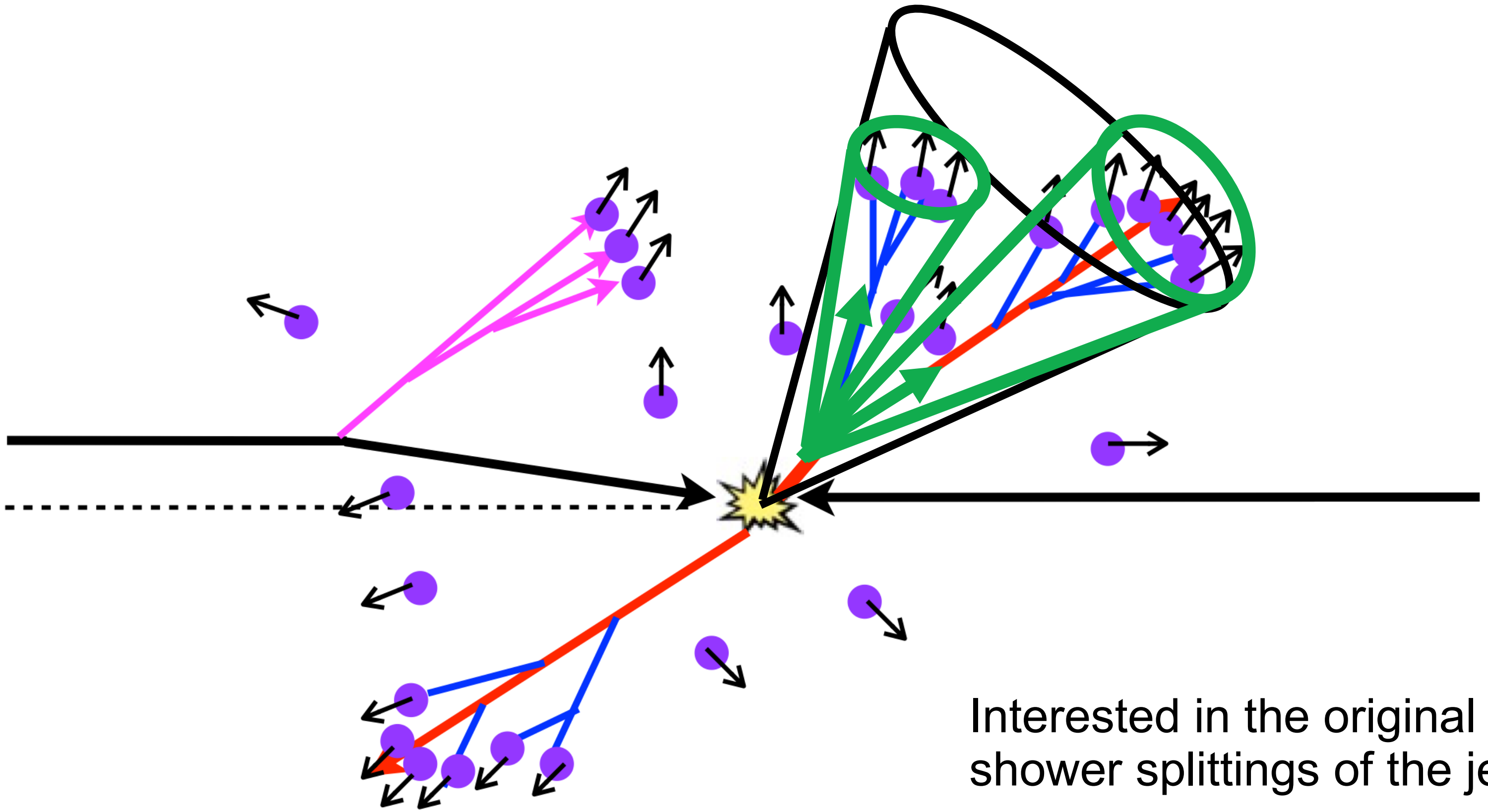
Agrees with PYTHIA

Type IV: Declustering

Note: These slides are from Laura Havener

*A selection. Don't be offended if I skip your favorite.

New tool: jet splittings



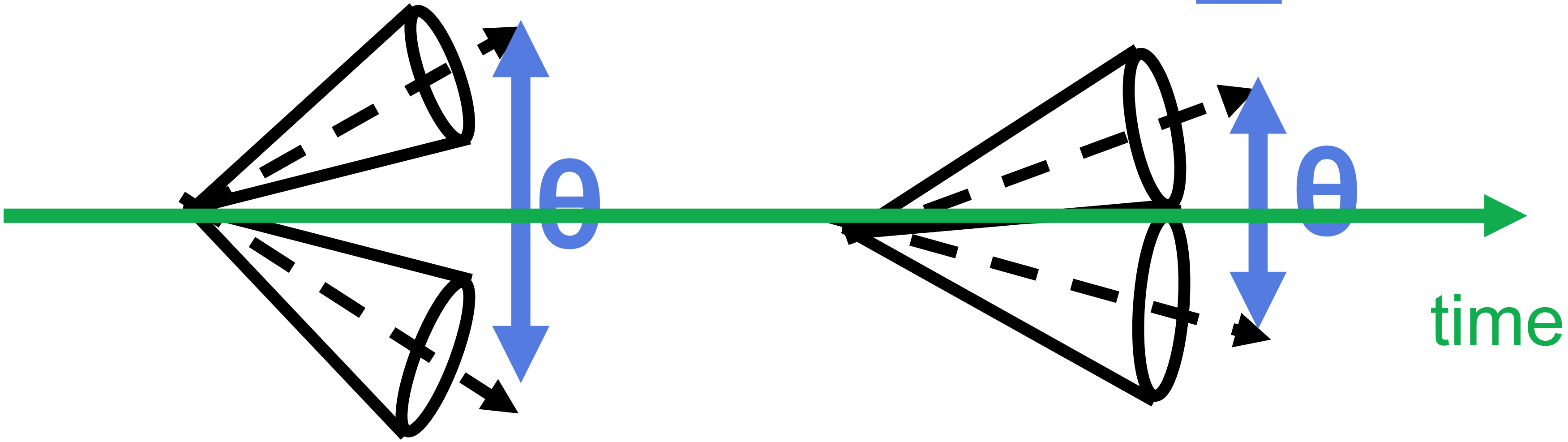
Interested in the original parton shower splittings of the jet

Which form subjets inside the jet!

Jet splittings: in vacuum

Vacuum jets splittings form at different times

$$t_f^{\text{vac}} = \frac{1}{\theta^2 \omega}$$

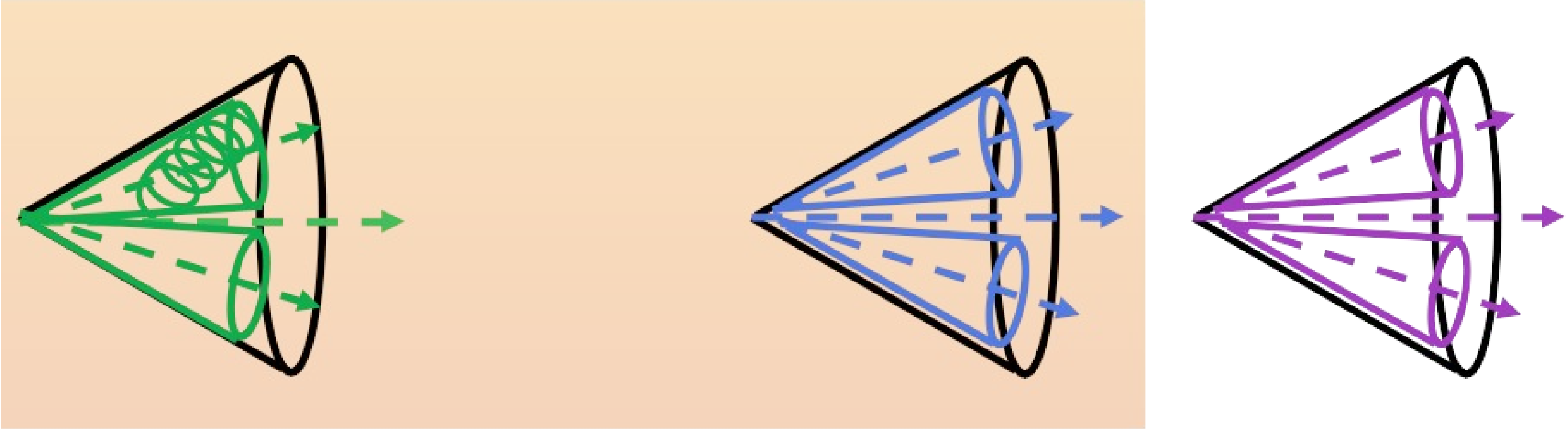


Wider jets form earlier and narrower jets form later

Jet splittings: in medium

Vacuum splittings in/out of the medium

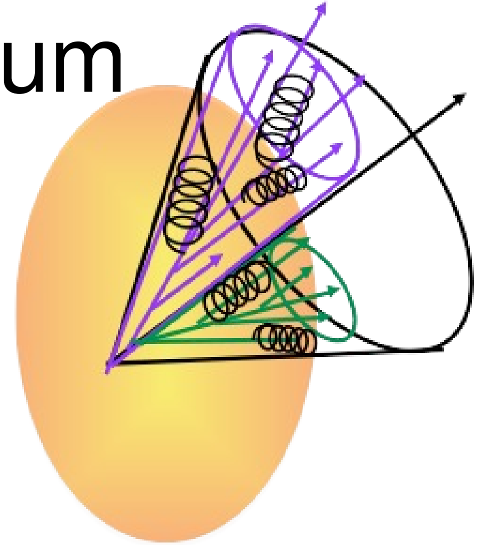
$$t_f^{\text{vac}} = \frac{1}{\theta^2 \omega}$$



Medium-induced splittings from gluon radiation

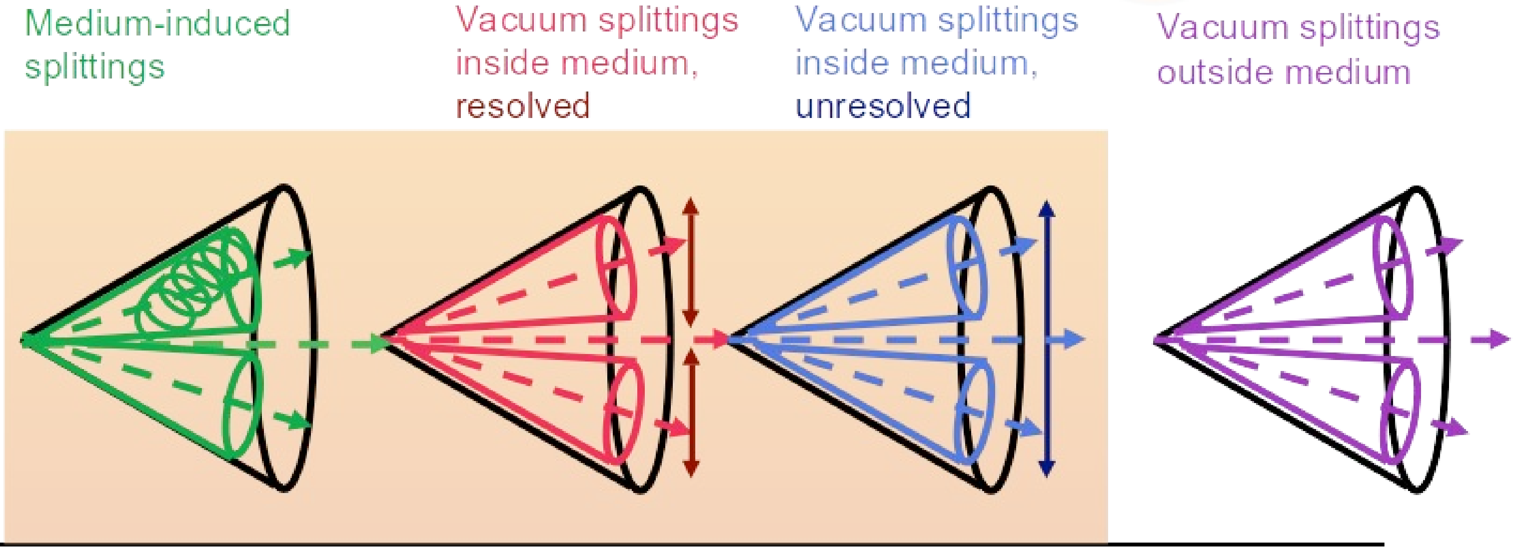
$$t_g^{\text{med}} = \sqrt{\frac{\omega}{\hat{q}}}$$

Jet splittings: in medium



Coherence: subjets *unresolved* and jet loses energy as a whole

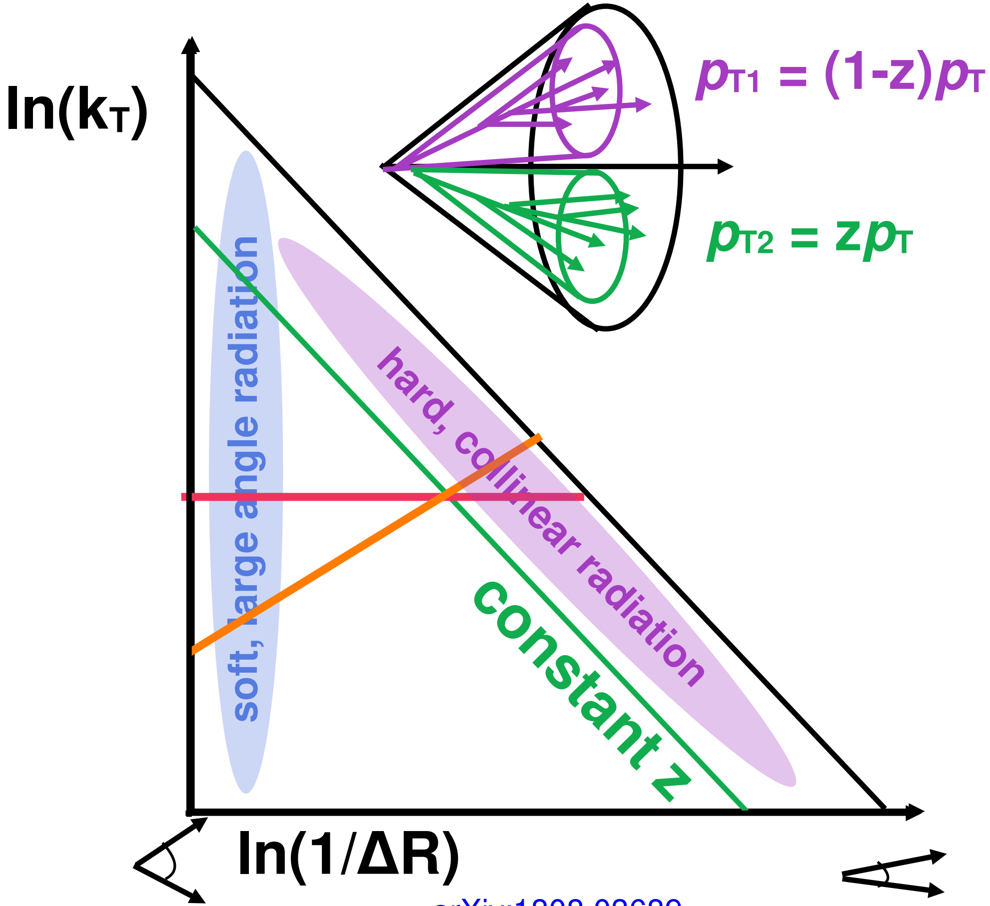
Decoherence: medium *resolves* the subjets resulting in a stronger e-loss



Exploring the Lund Plane: in vacuum

- Lund Diagram*: phase space of jet splitting
  [*Z. Phys. C43 (1989)](#)
  [JHEP 12 (2018)](#)
- $\log(k_T) > 0$ separates perturbative from non-perturbative regime
- Formation time: how long until the splitting occurred $t_f = \frac{1}{(1-z)k_T\Delta R}$

Y. L. Dokshitzer, et.al.

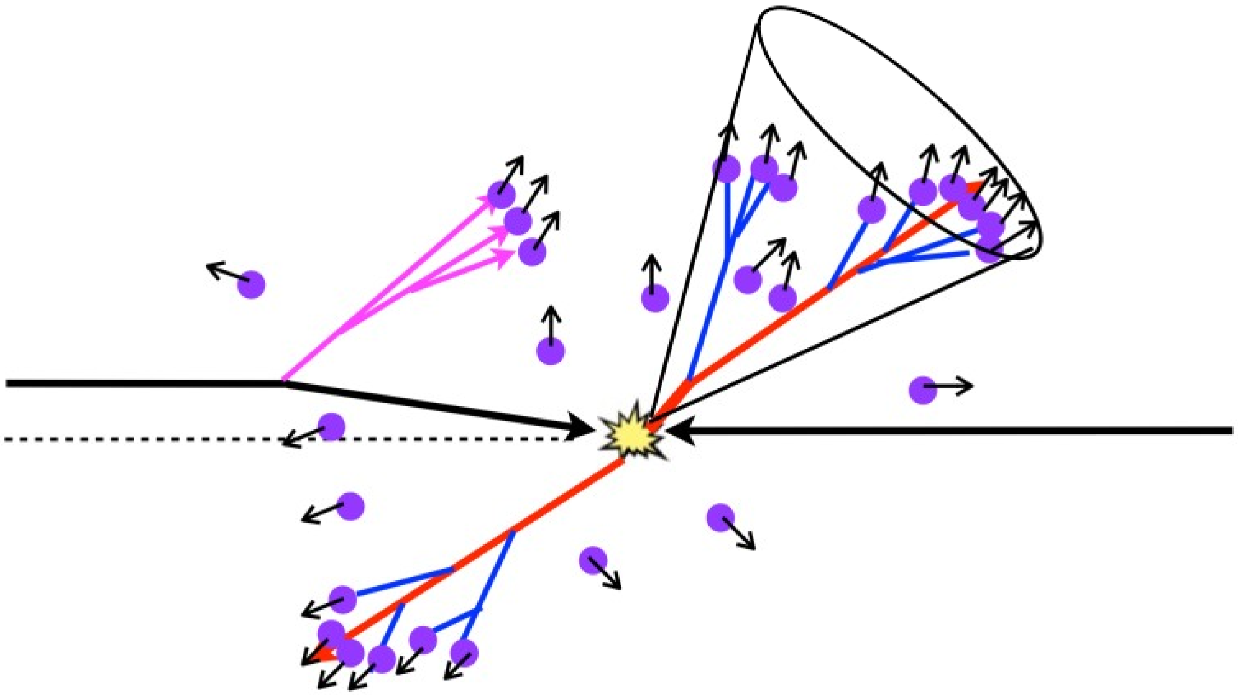


arXiv:1808.03689

Soft drop grooming

- Reconstruct anti-k_T R=0.4 charged jets with jet-by-jet constituent background subtraction*

*JHEP 06 (2014) 092



Soft drop grooming

- Reconstruct anti-k_T R=0.4 charged jets with *jet-by-jet constituent background subtraction**

*JHEP 06 (2014) 092

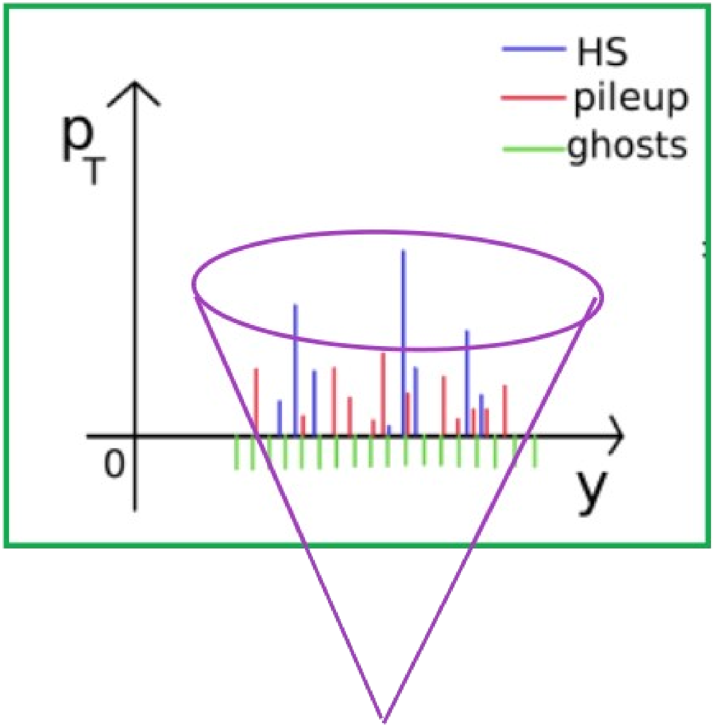
Remove from each constituent inside the jet instead of from the whole jet

Jet-by-jet:

$$p_T^{\mathrm{jet,corr}} = p_T^{\mathrm{jet}} - \rho A$$

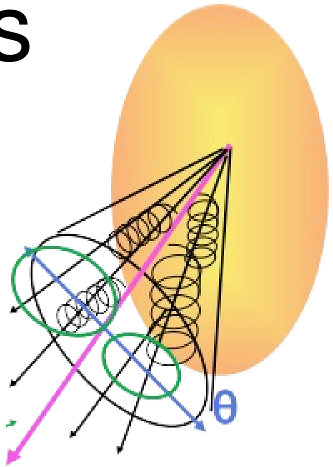
Track-by-track (i) in jet:

$$p_T^{\mathrm{i,corr}} = p_T^{\mathrm{i}} - \rho A$$

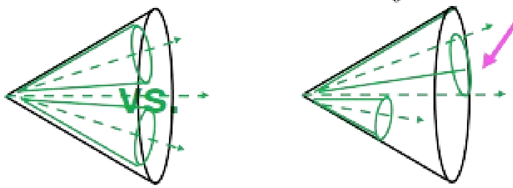


Groomed variables

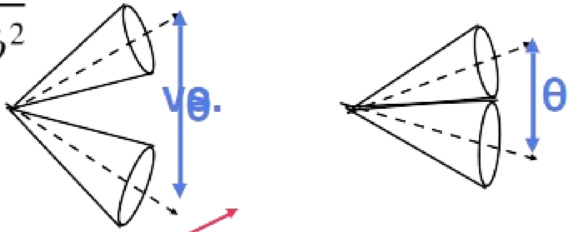
- Soft drop grooming variables probe jet splitting
  - ➡ z_g: shared momentum fraction between two hardest subjets in parton shower $z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$



How symmetric is the jet splitting?



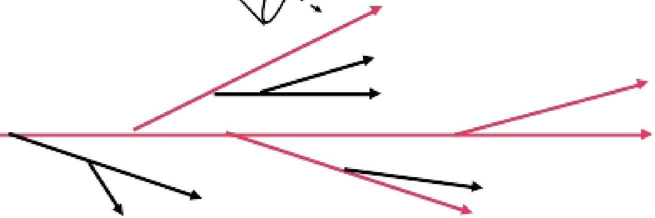
  - ➡ R_g: distance between subjets $R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



How far apart are the subjets?

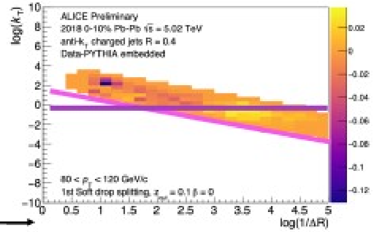
  - ➡ n_{SD}: number of splittings passing Soft Drop

Number of subjets within a jet?

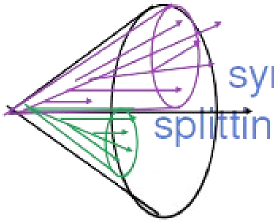


z_g: jet splitting

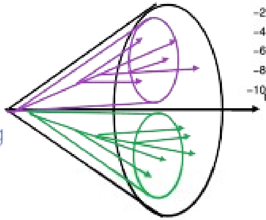
$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

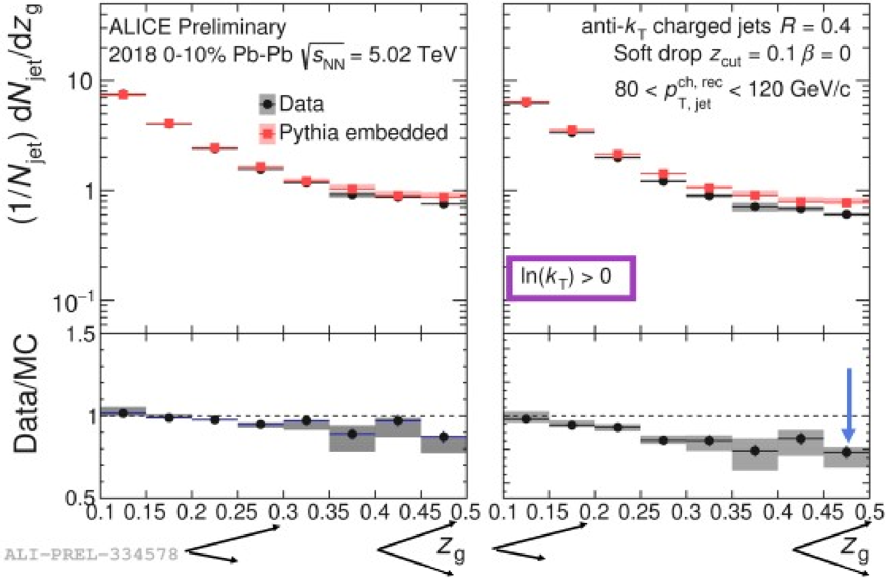


asymmetric splitting: low z_g



symmetric splitting: high z_g

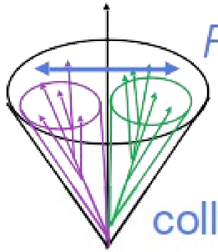


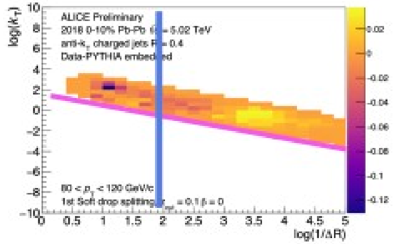


Suppression of symmetric splittings

z_g: opening angle

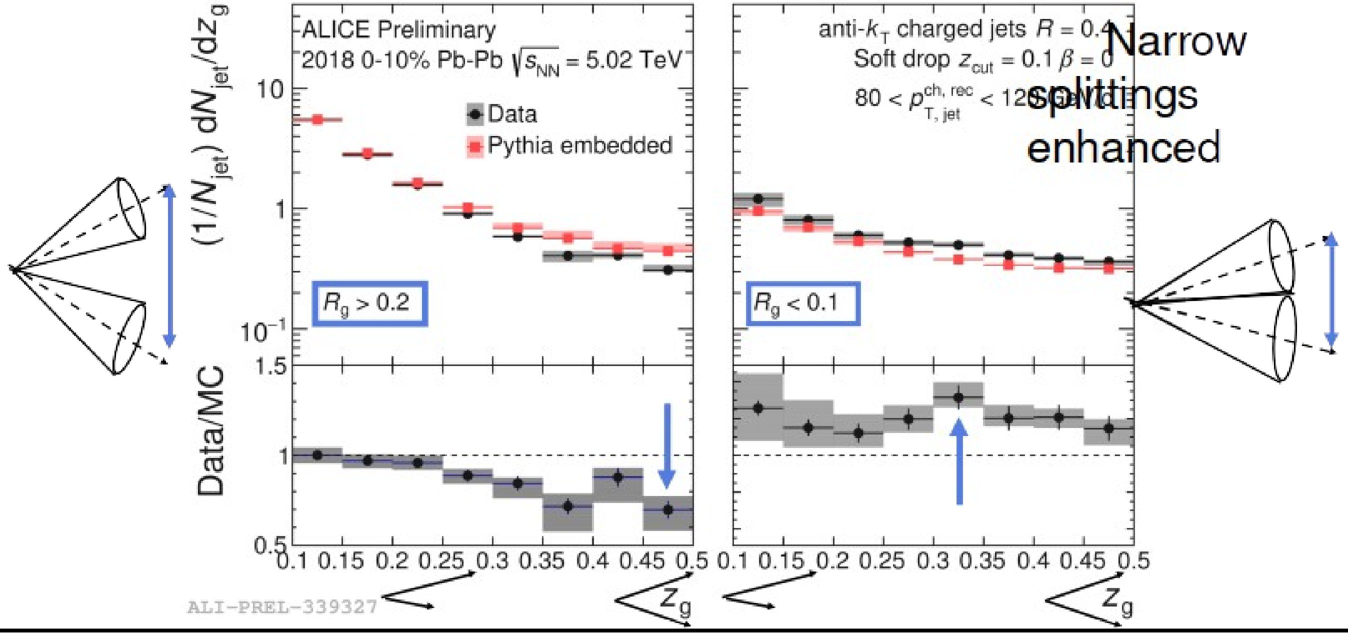
Wide: more significant suppression of symmetric splittings





wide $R_g > 0.2$

collimated $R_g < 0.1$



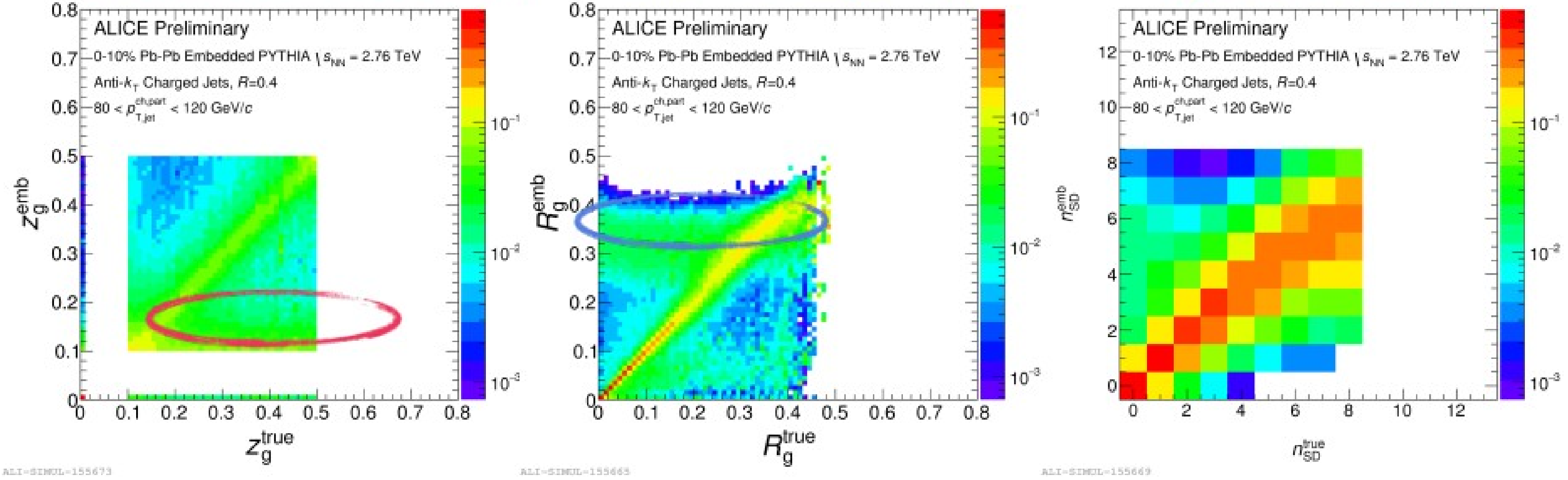
Narrow splittings enhanced

Background

Unfolding: jet splitting

Uncorrelated background leads to subjets being picked up as incorrect or “fake” splittings

dominate at low z_g | and at large R_g | gone in n_{SD}?



Non-diagonal response prohibits unfolding

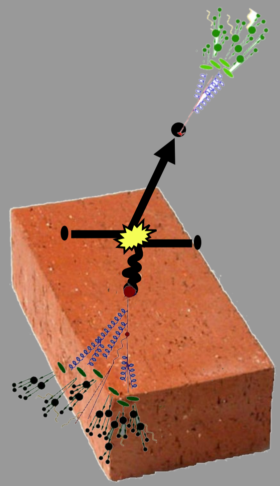
Mini-summary

- “Jet substructure” is used inconsistently
- Search for new observables
  - Haven’t really used most of the “old” ones!
- So far it’s a mixed bag
  - Many are insensitive
  - Some may have some promise
  - Background tricky

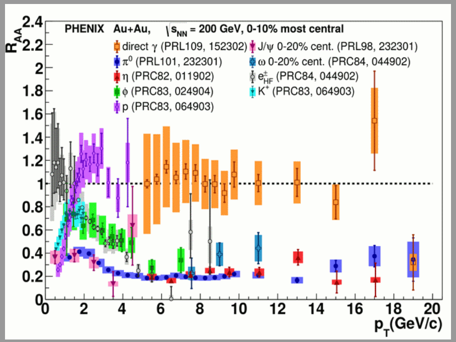
JETSCAPE

JET collaboration

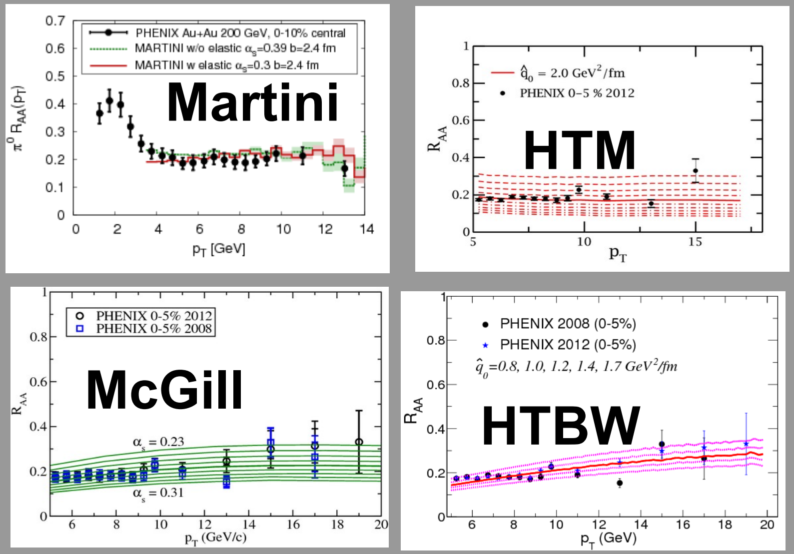
Phys. Rev. C 90, 014909 (2014)

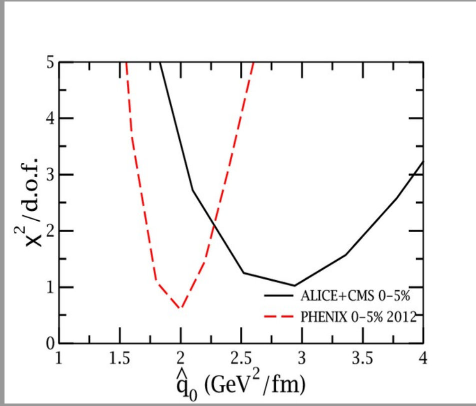


QGP brick + jet

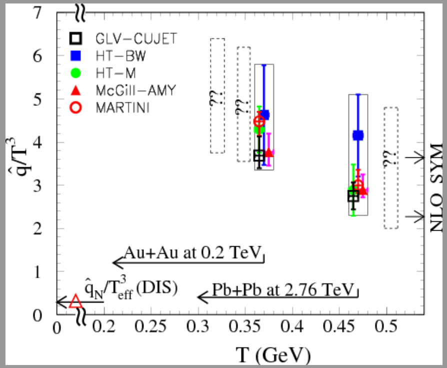


Data





χ^2 *minimization*



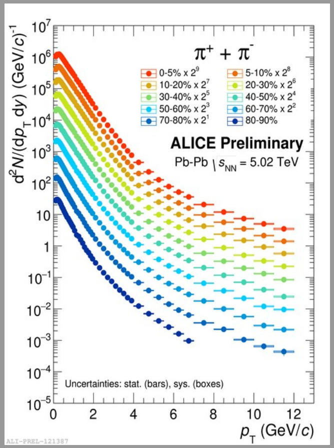
$\hat{q}=1.2\pm0.3\ \ GeV^2$ 200 GeV Au+Au

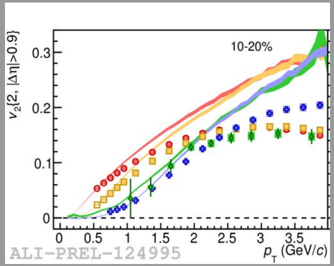
$\hat{q}=1.9\pm0.7\ \ GeV^2$ 2.76 TeV Pb+Pb

Bayesian Statistical Analysis

Models and Data Analysis Initiative

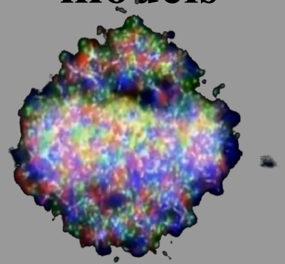
http://madai.us





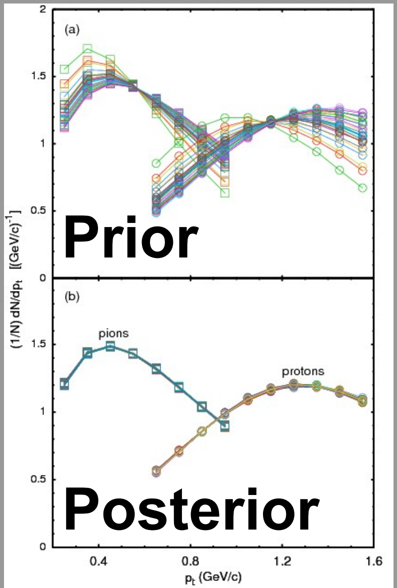
Data

Monte Carlo models

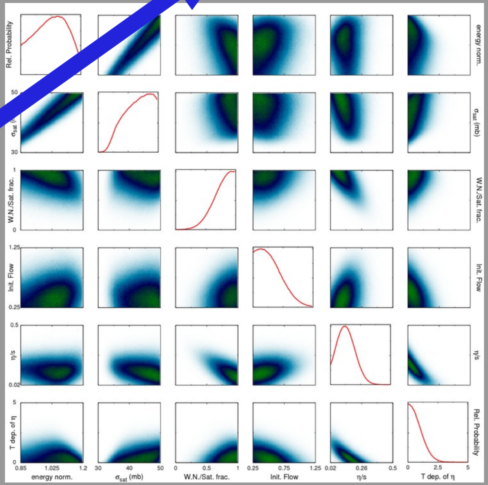


Model emulation

1) Run full model ~1000 times
2) MCMC parameter search uses emulator (interpolator) in lieu of full model



Optimization



Constraint of QGP properties

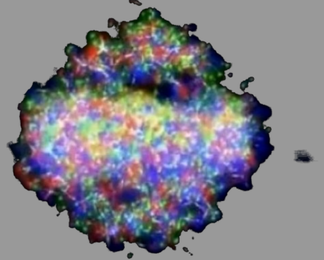
Novak et al, Phys.Rev. C89 (2014) no.3, 034917

JETSCAPE Event generator

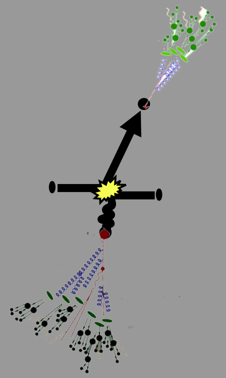
Jet **E**nergy-loss **T**omography with a **S**tatistically and **C**omputationally **A**dvanced **P**rogram **E**nvelope

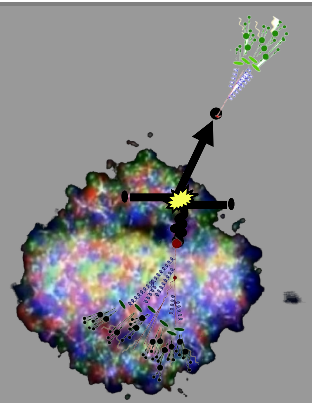
http://jetscape.wayne.edu/

Realistic medium



Realistic jets





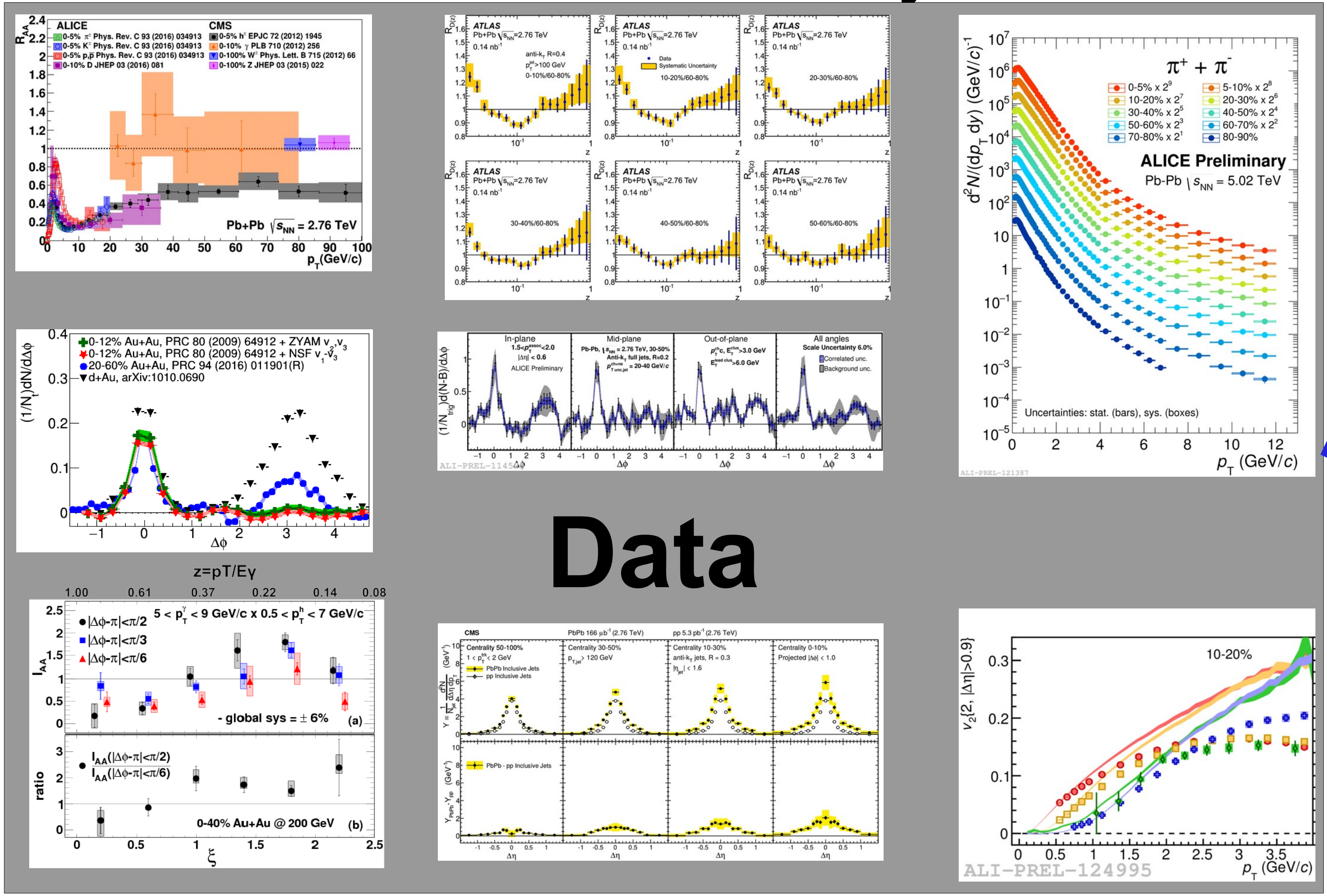
Realistic Monte Carlo Model

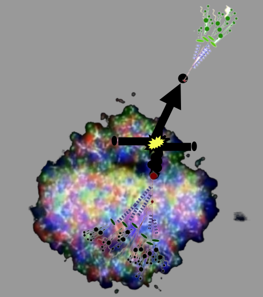
Experimental techniques

Realistic theoretical calculations

JETSCAPE

Event Generator + Bayesian Statistical analysis





Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties

Conclusions

Conclusions

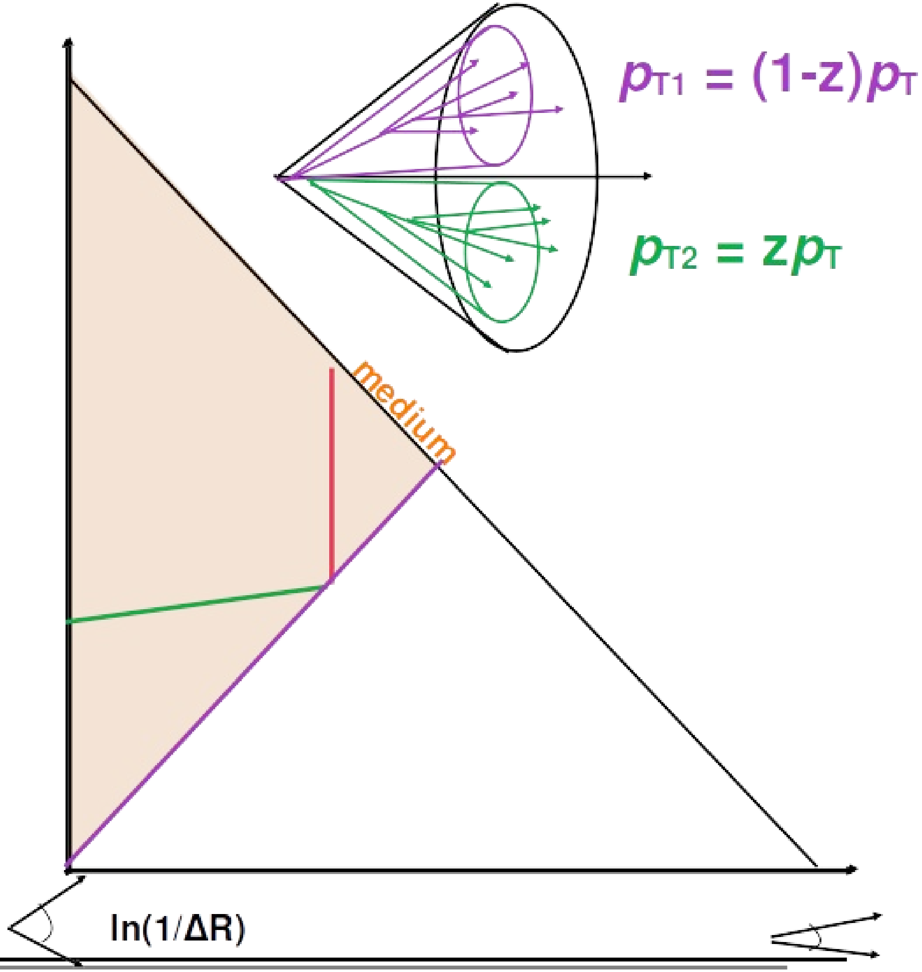
- Jets are complicated and hard to measure to high precision
- Much of the physics we want does not require them
- Extra insight from studying them anyways
- Be skeptical, especially of background subtraction
- Make sure the measurement is comparable to model

The End

Backup

Exploring the Lund Plane: in medium

- Jet splittings in heavy-ion (HI) collisions
  - ➡ Splittings happen at different times
    - Earlier/wider splittings experience more medium
  - ➡ Vacuum splittings vs. non-perturbative in-medium splittings
  - ➡ Coherence vs. decoherence



Exploring the Lund Plane: in medium

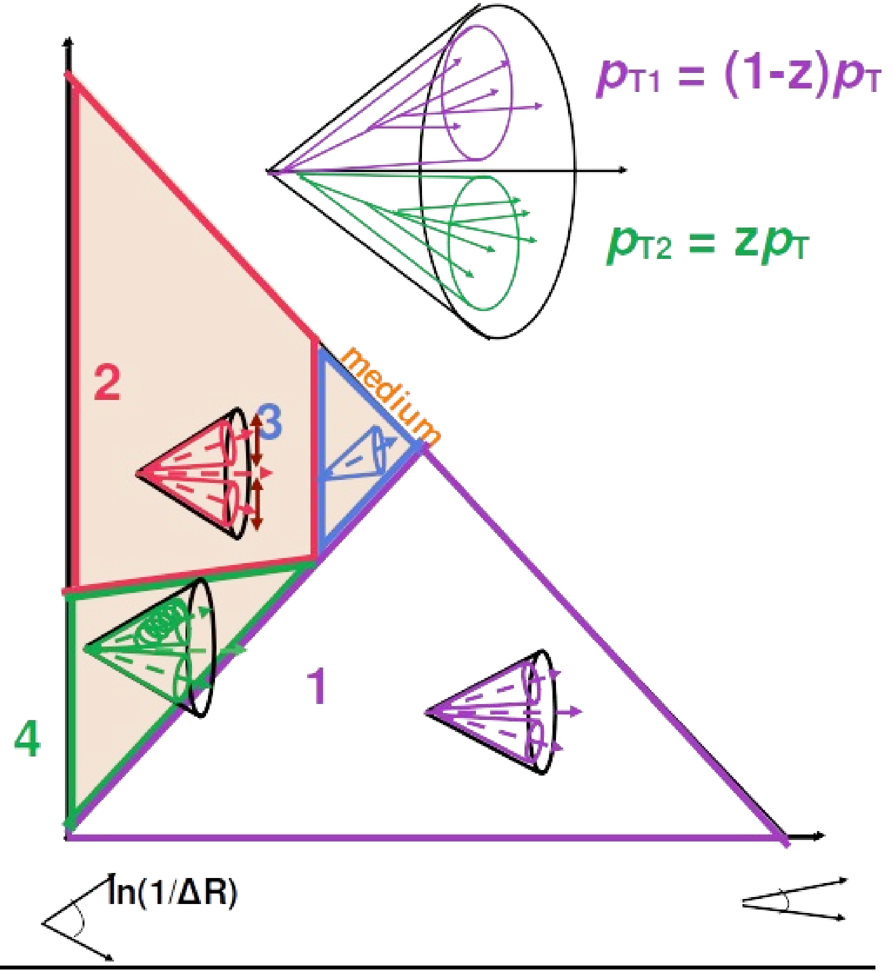
- Jet splittings in heavy-ion (HI) collisions

1: Vacuum splitting outside of medium

2: Vacuum splitting in-medium, resolved (decoherence)

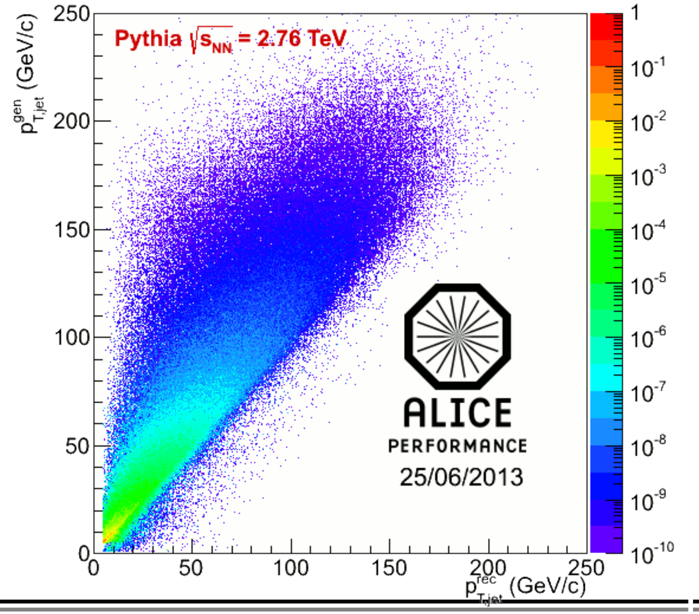
3: Vacuum splittings in-medium, unresolved (coherence)

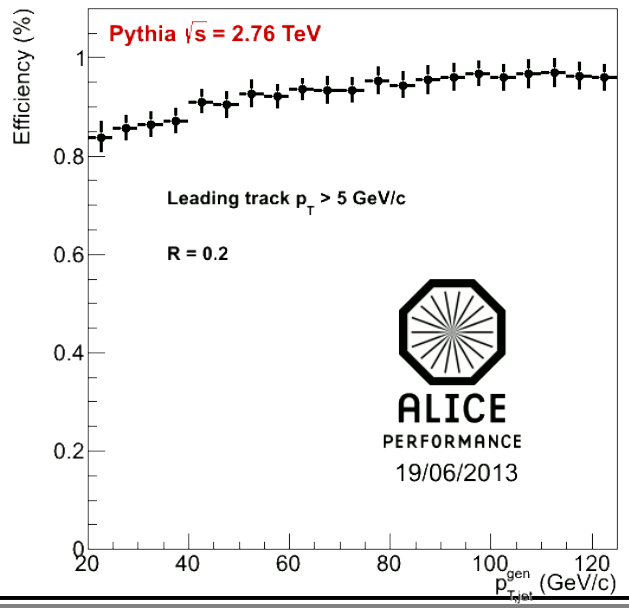
4: Medium-induced splittings

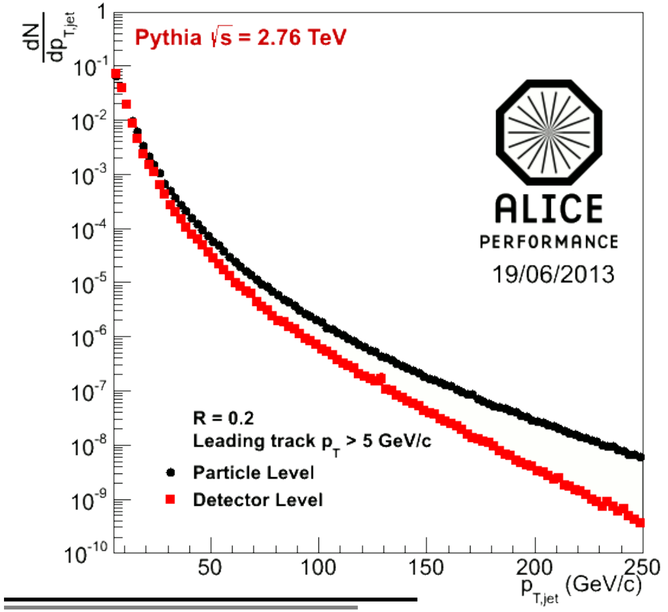


Jets in ALICE: Response matrix RM_{det}

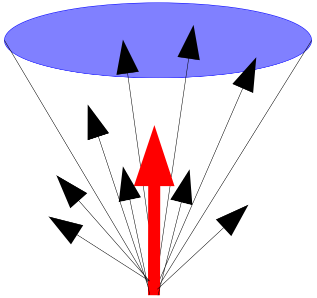
- RM_{det} quantifies detector response to jets
  - “Particle” level jets – defined by jet finder on MC particles
  - Pythia with Pb-Pb tracking efficiency
  - “Detector” level jets – defined by jet finder after event reconstruction through GEANT
  - Particle level jets are geometrically matched to detector level jets
  - Matrix has a dependence on spectral shape and fragmentation
- Jet-finding efficiency is probability of a matched particle level jet

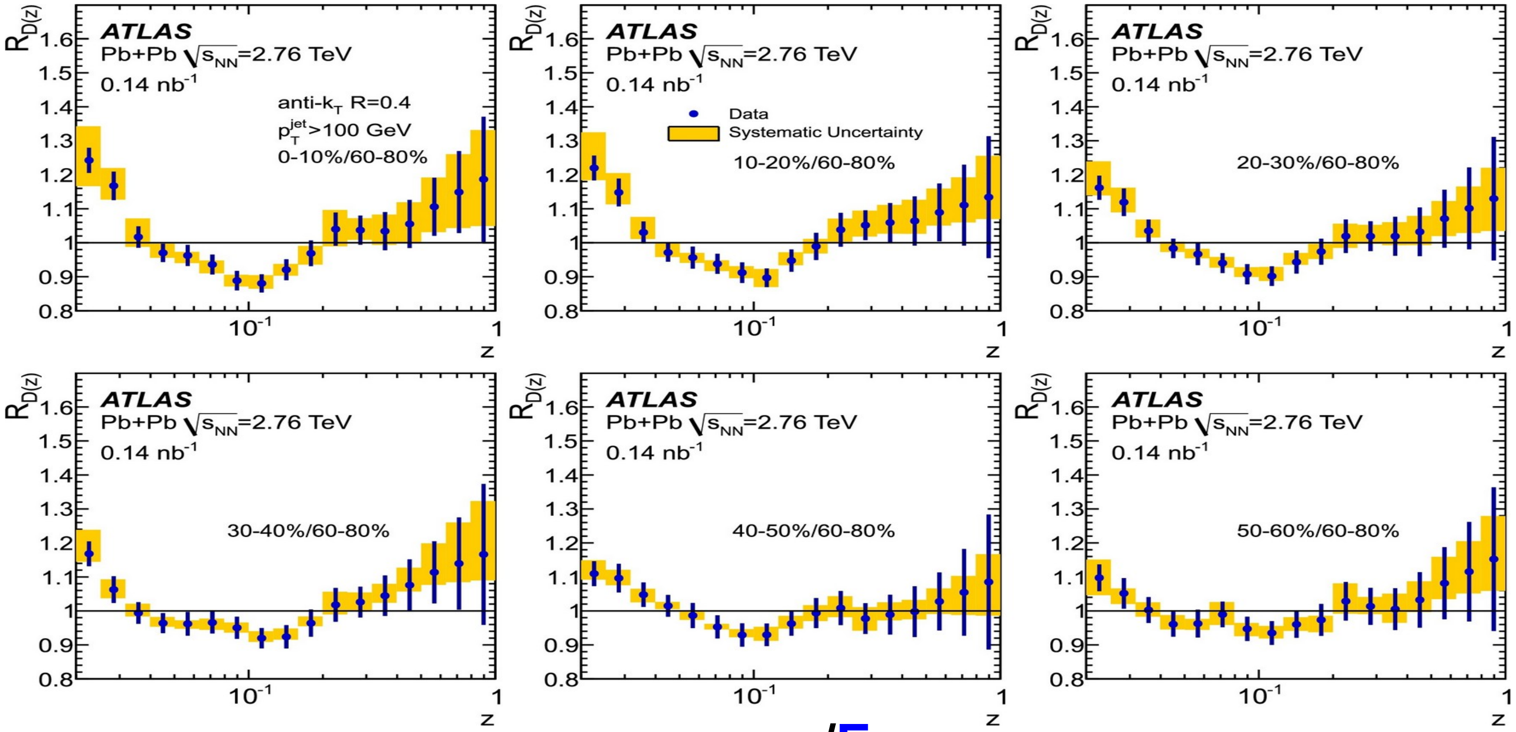






Modified fragmentation





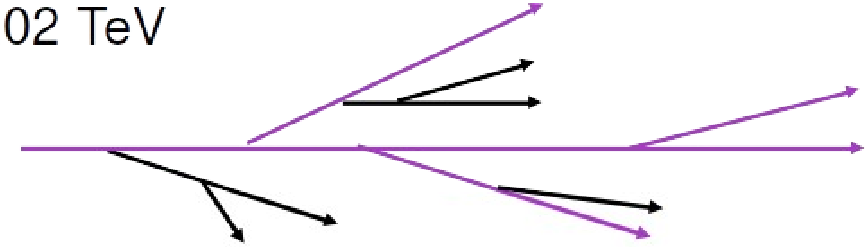
$z = p_T / E_\gamma$

- Enhancement at low z
- No modification/enhancement at high z?

n_{SD}: iterative declustering

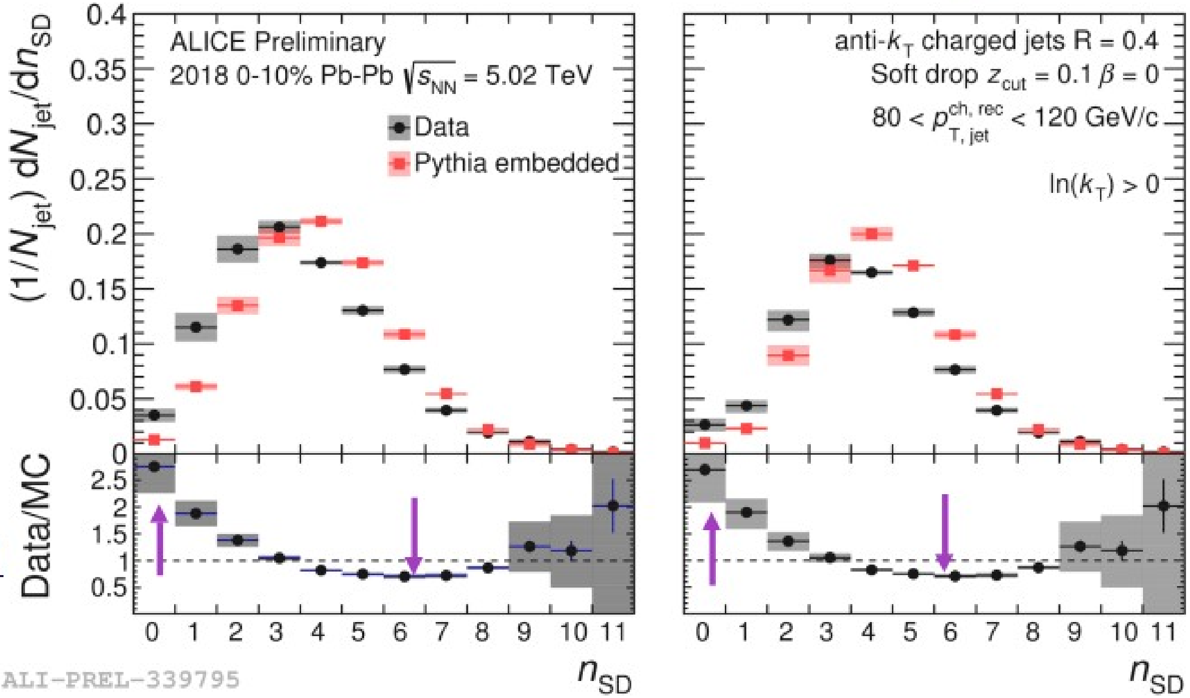
New ALICE measurement at 5.02 TeV

Modification: enhancement at small n_{SD} and suppression at intermediate n_{SD}



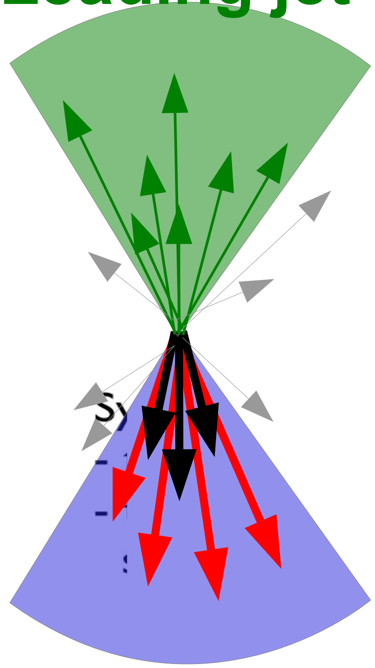
Consistent with wider/earlier being suppressed in the medium, leading to more jets with lower n_{SD}*

*arXiv:1907.11248v1



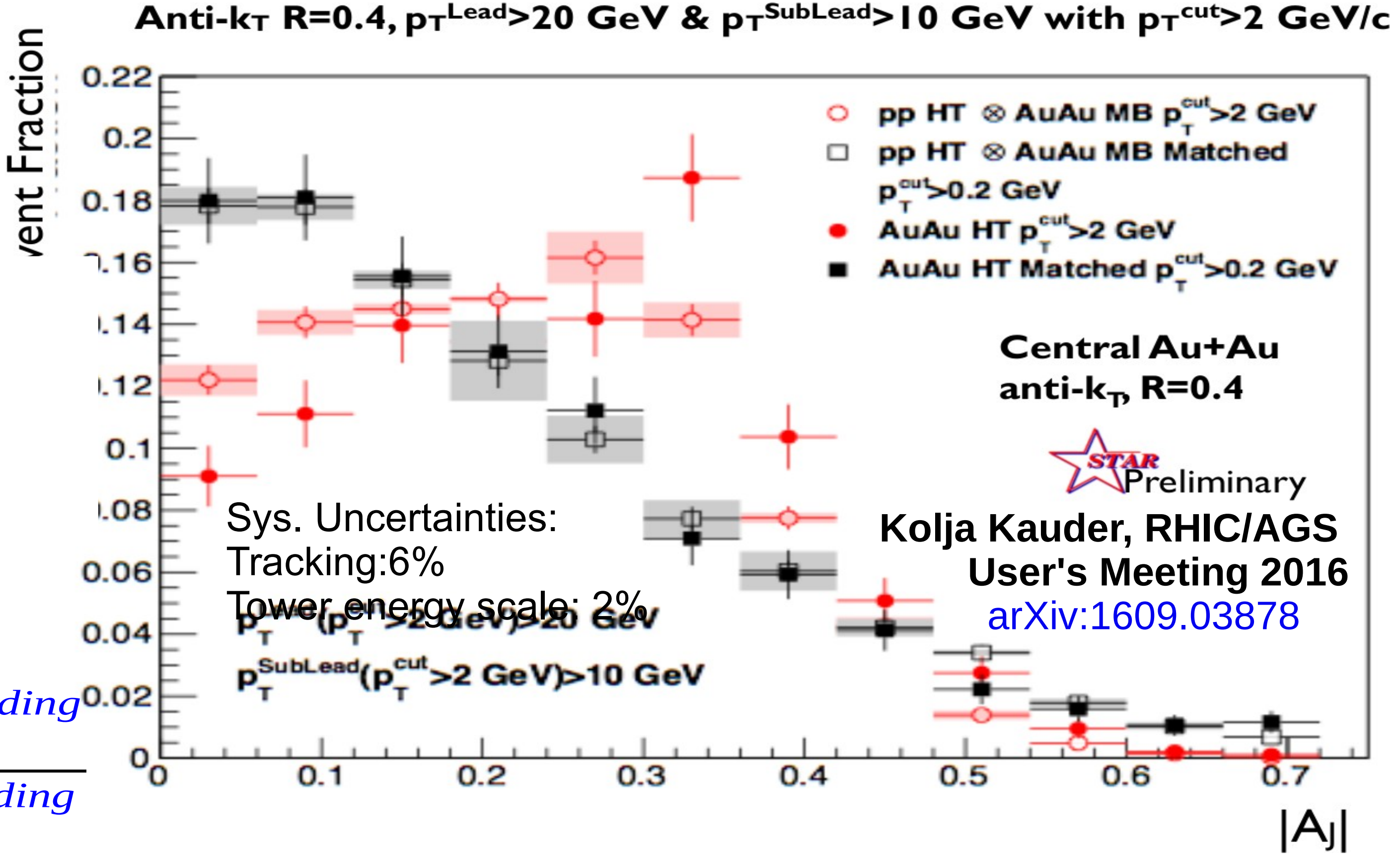
Di-jet asymmetry

Leading jet



Subleading jet

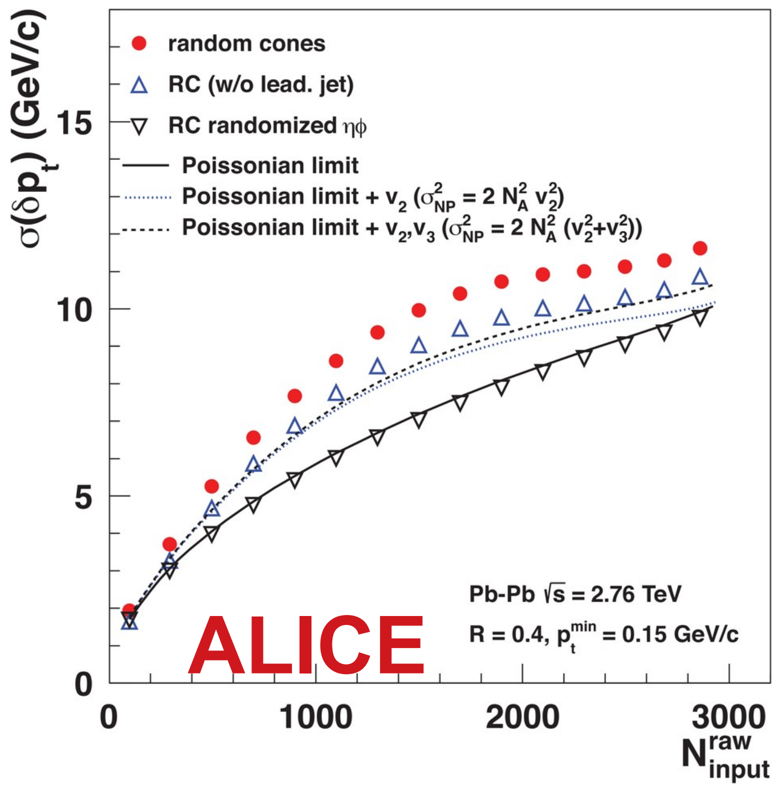
$$A_j = \frac{p_T^{leading} - p_T^{subleading}}{p_T^{leading} + p_T^{subleading}}$$

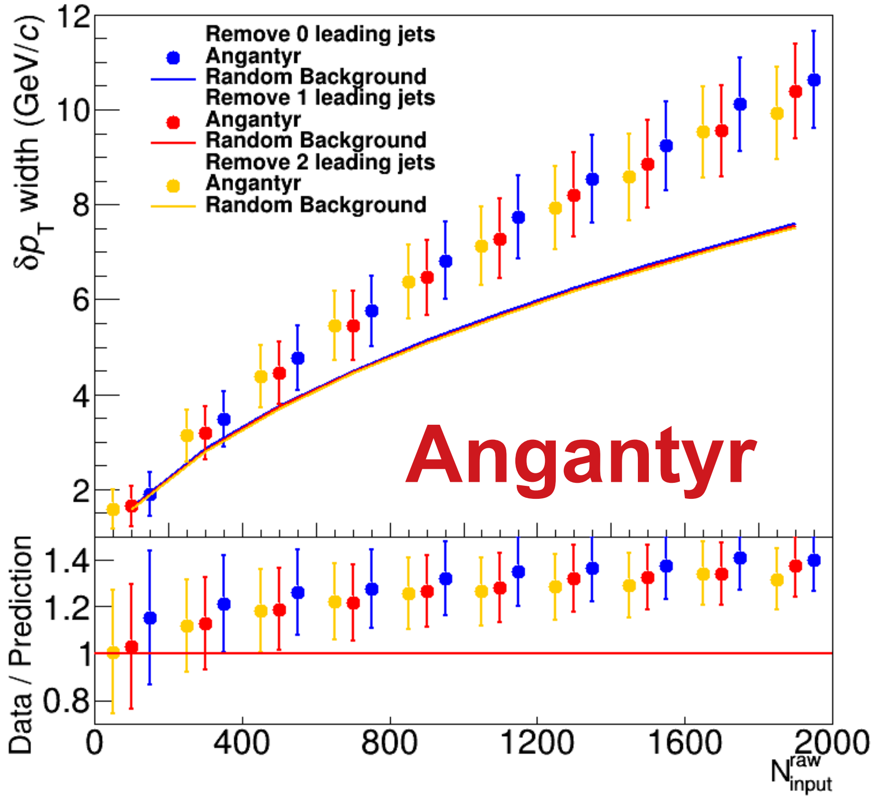


Au+Au di-jets more imbalanced than p+p for p_{Tcut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

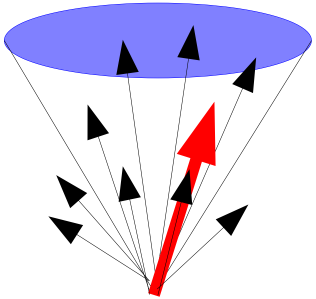
Width vs multiplicity

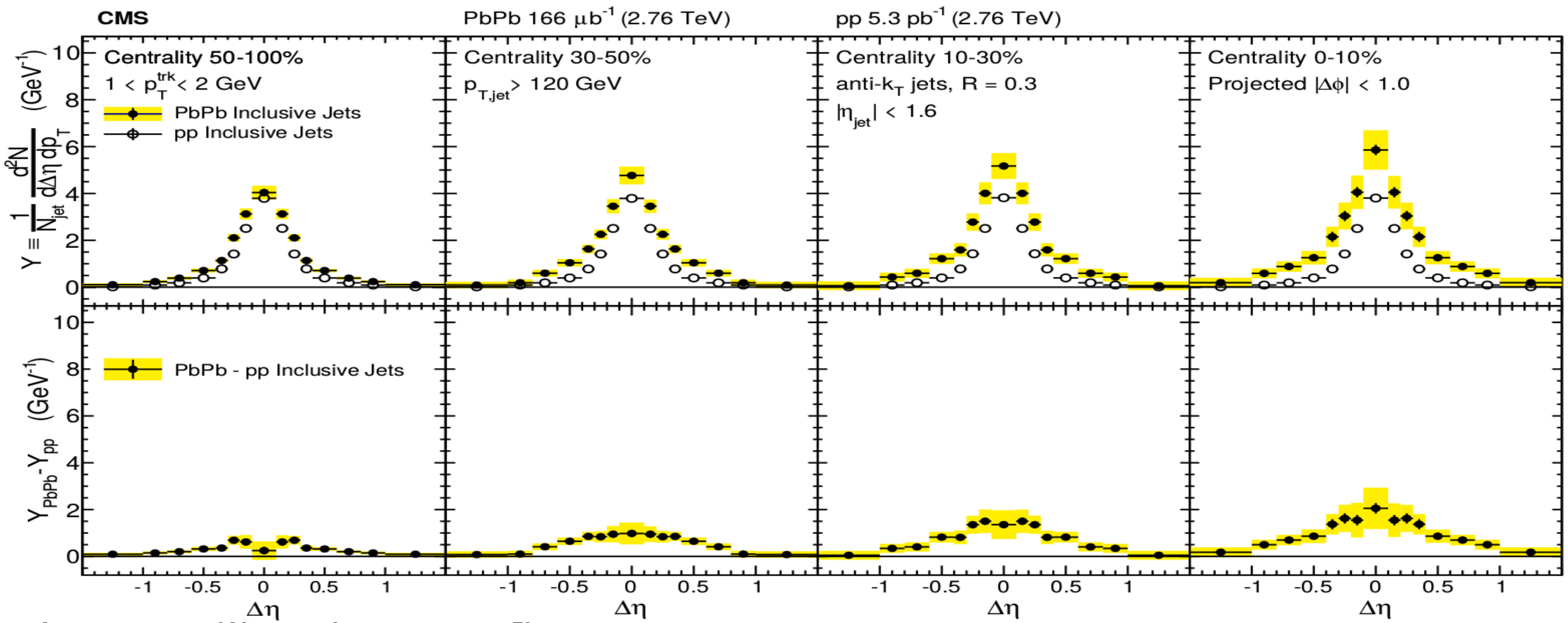




Discrepancy not from an excess of jets!

Jet-hadron correlations





- Jets are broader, constituents are softer
- Also seen in:
  - Di-hadron correlations [Lots of papers]
  - Jet shapes [arXiv:1708.09429, arXiv:1512.07882, arXiv:1704.03046]
  - Dijet asymmetry with soft constituents [PRL119 (2017) 62301]