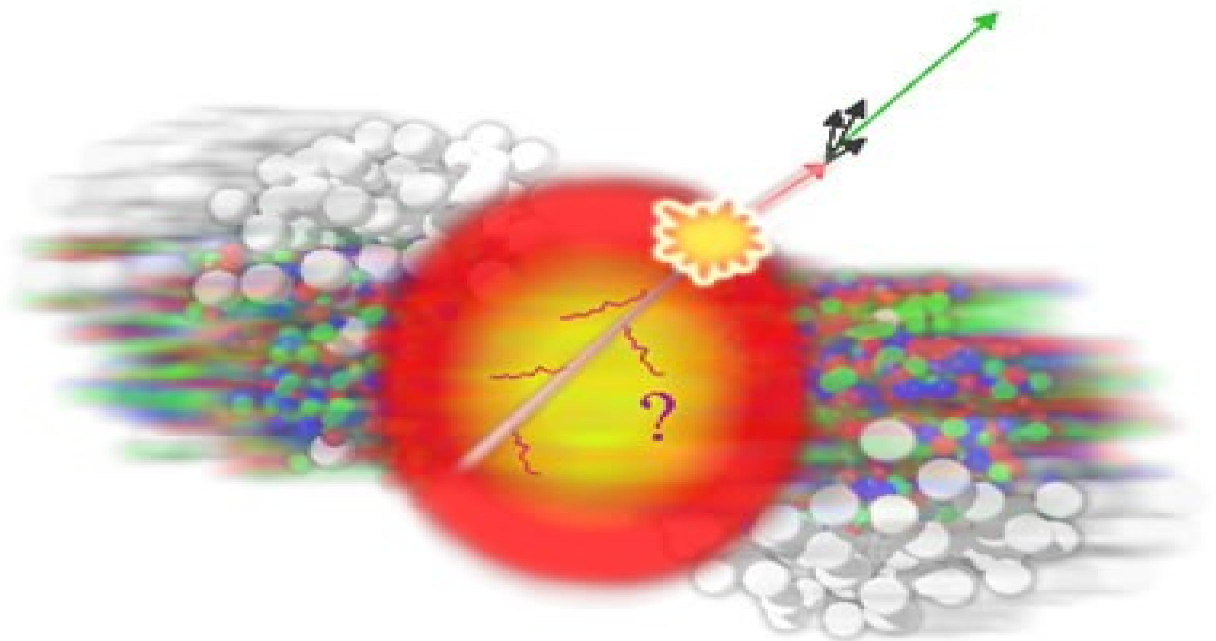
Jets for non-jet people



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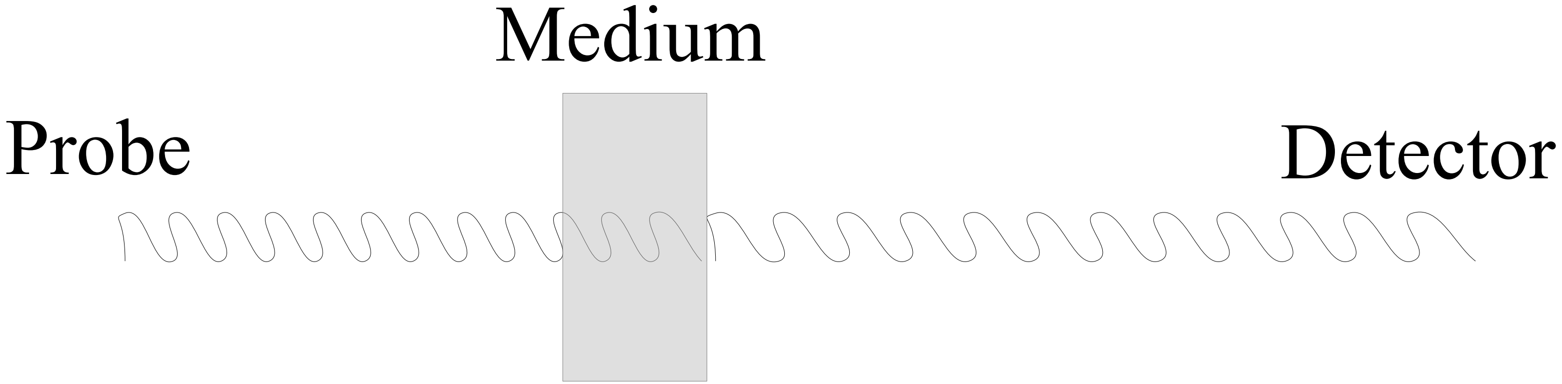
Acknowledgements

The following people contributed ideas and/or slides, but of course I take full responsibility for anything you don’t like:

Rosi Reed, Megan Connors, Sevil Salur
Abhijit Majumder, Raghav Kunnawalkam Elayavalli
Marta Verweij, Laura Havener
Austin Schmier, Charles Hughes, Will Witt

What do I want to learn?
The cartoon picture

Probing the Quark Gluon Plasma

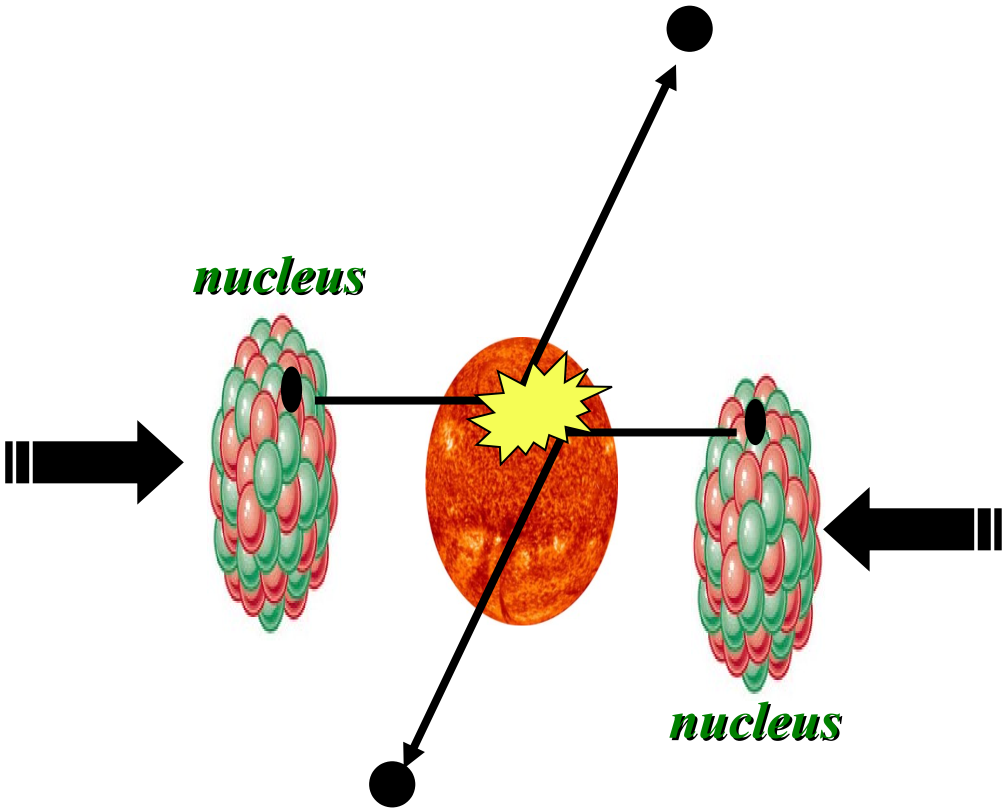


Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

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

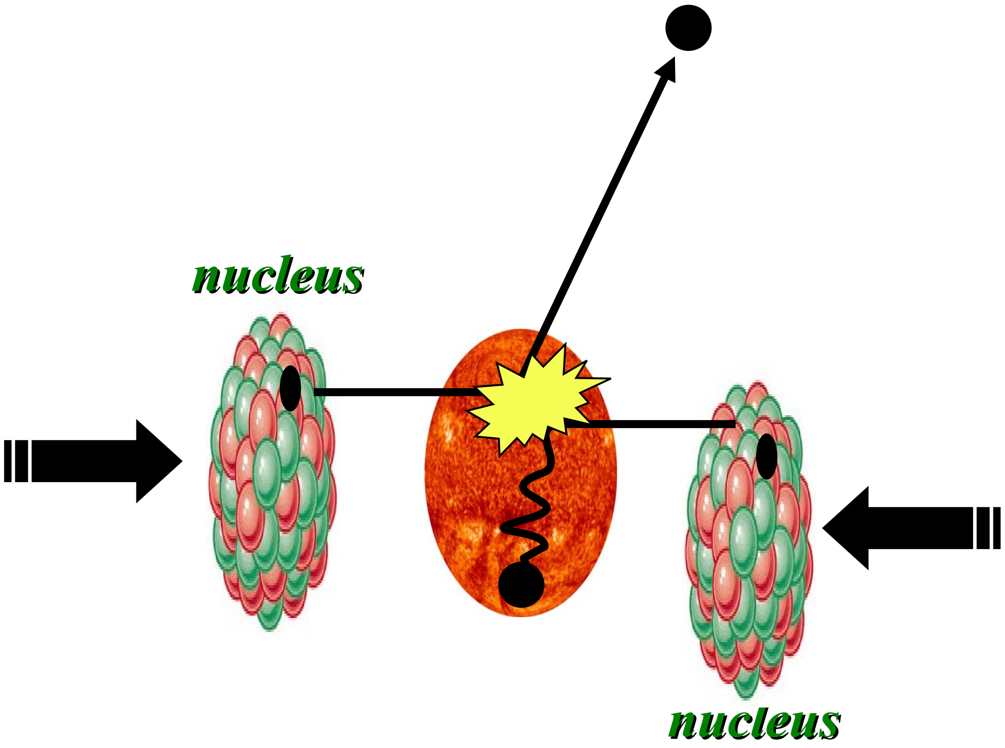


Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium

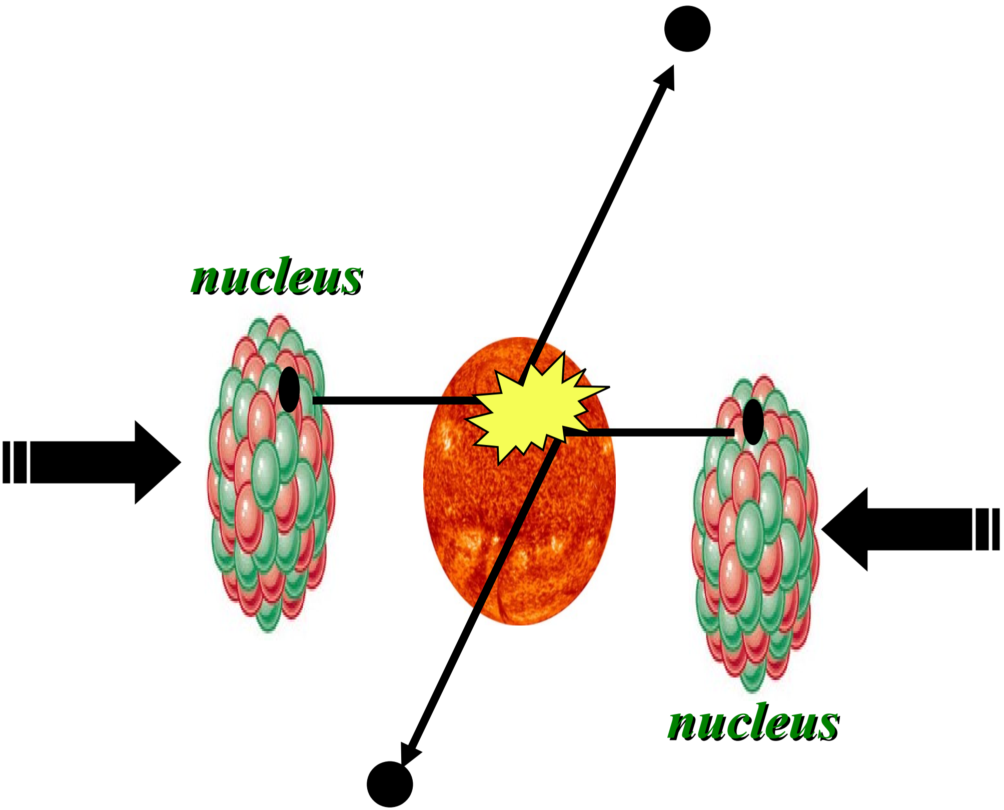
QGP is short lived → need a probe created in the collision

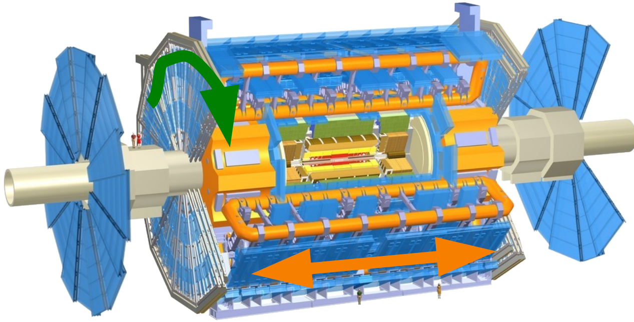
We expect the medium to be dense → absorb/modify probe

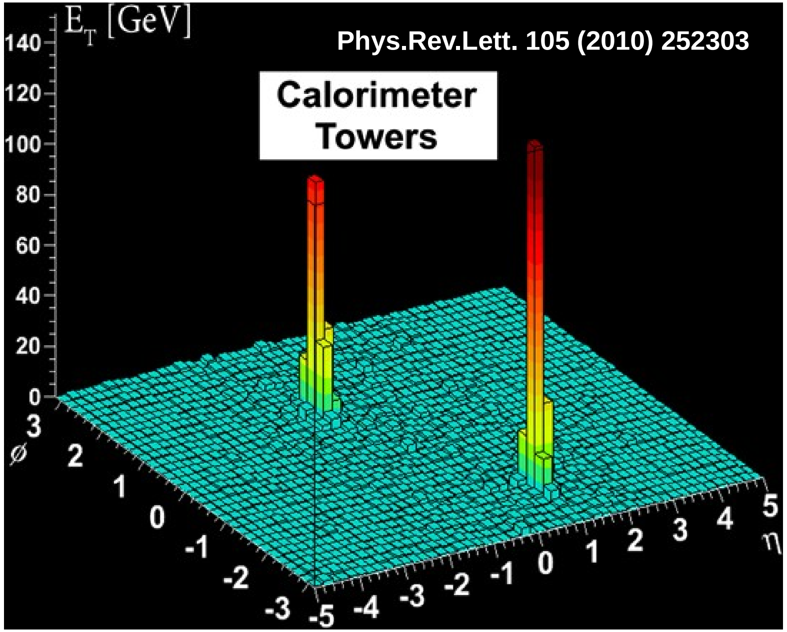


Probes of the Quark Gluon Plasma

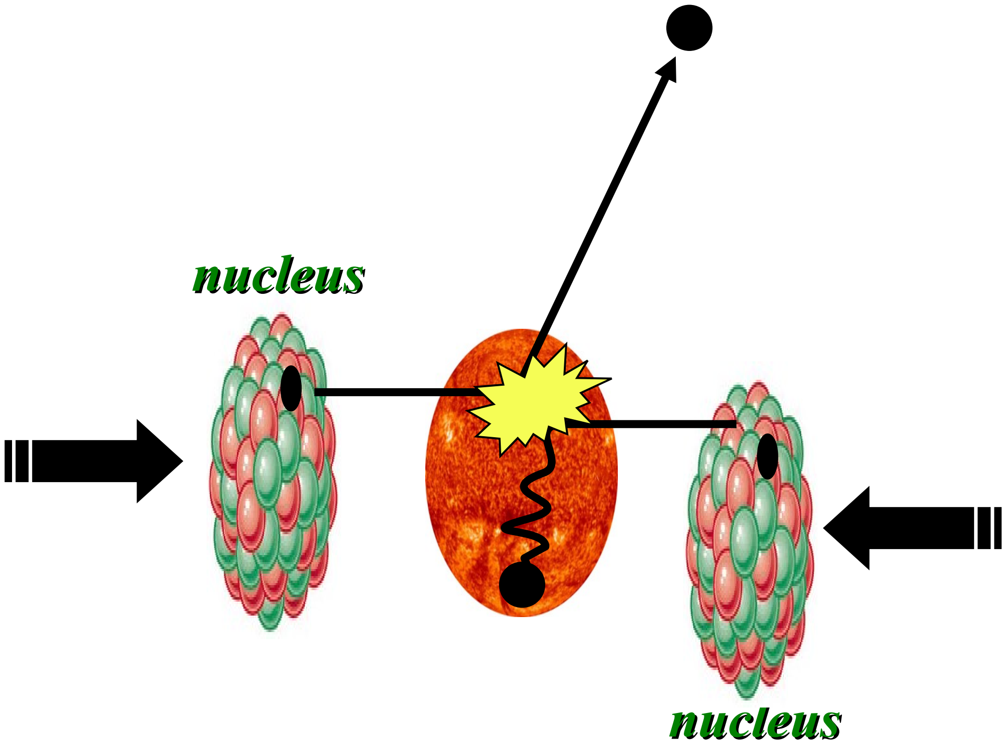
ATLAS

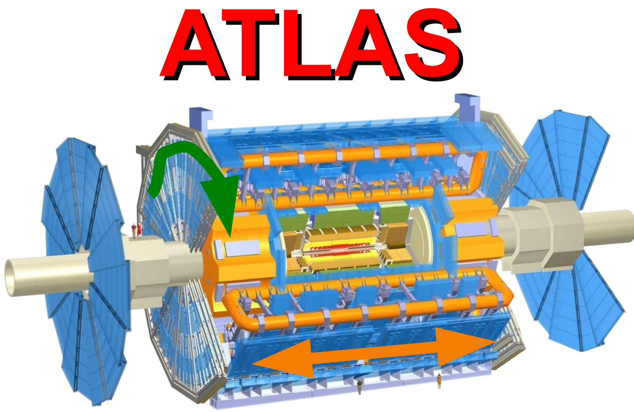


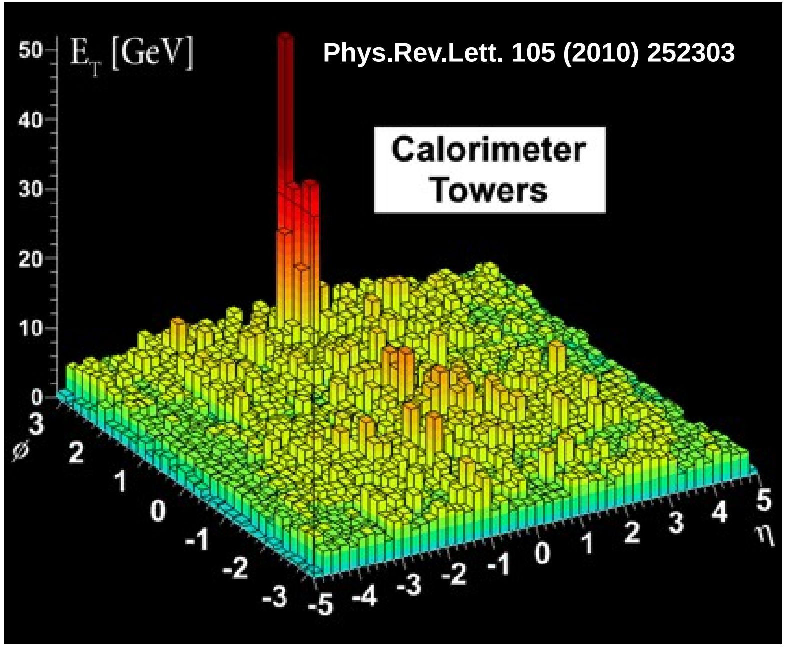




Probes of the Quark Gluon Plasma







What am I measuring?
Definition of a jet

Theory

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

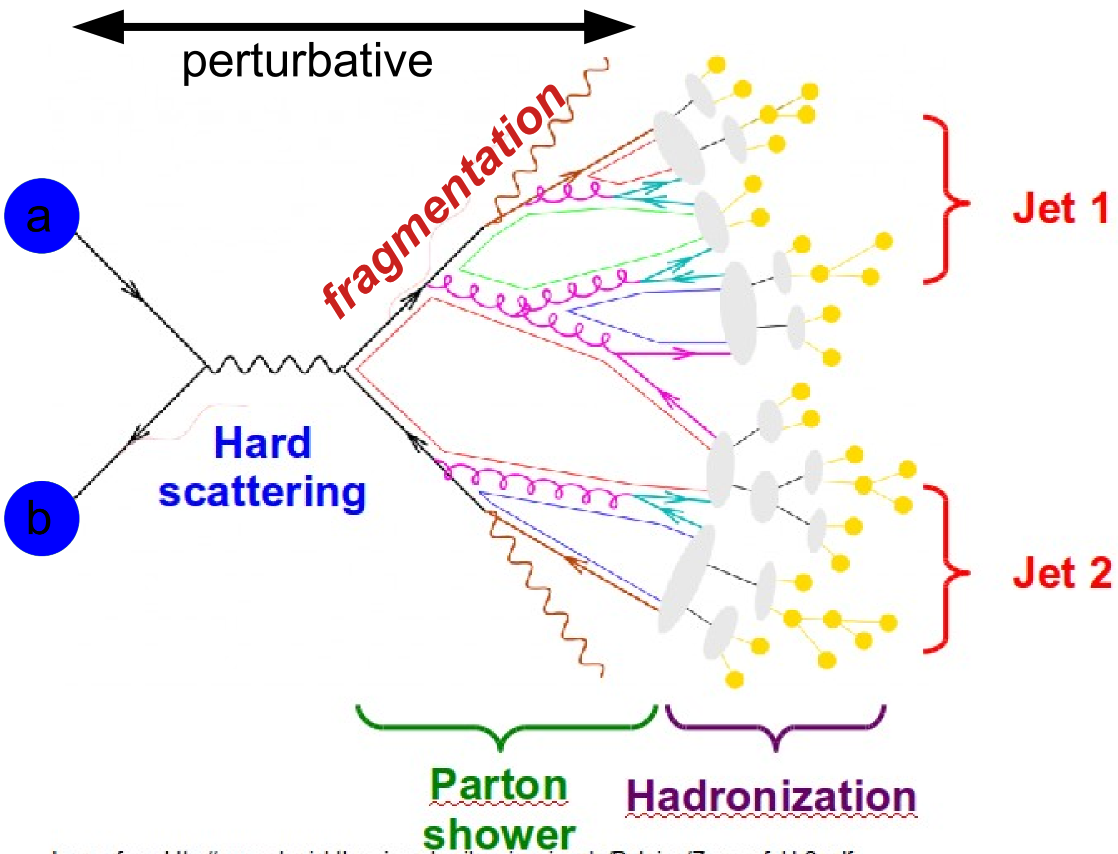


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

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

Jet finders

What is a jet?

What is a jet?

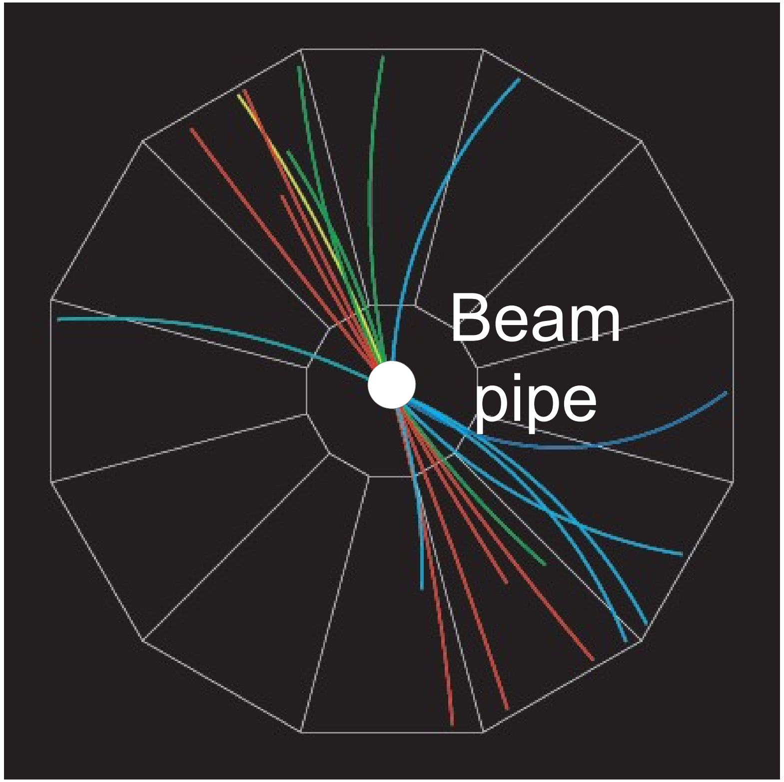
A measurement of a jet is a measurement of a parton.

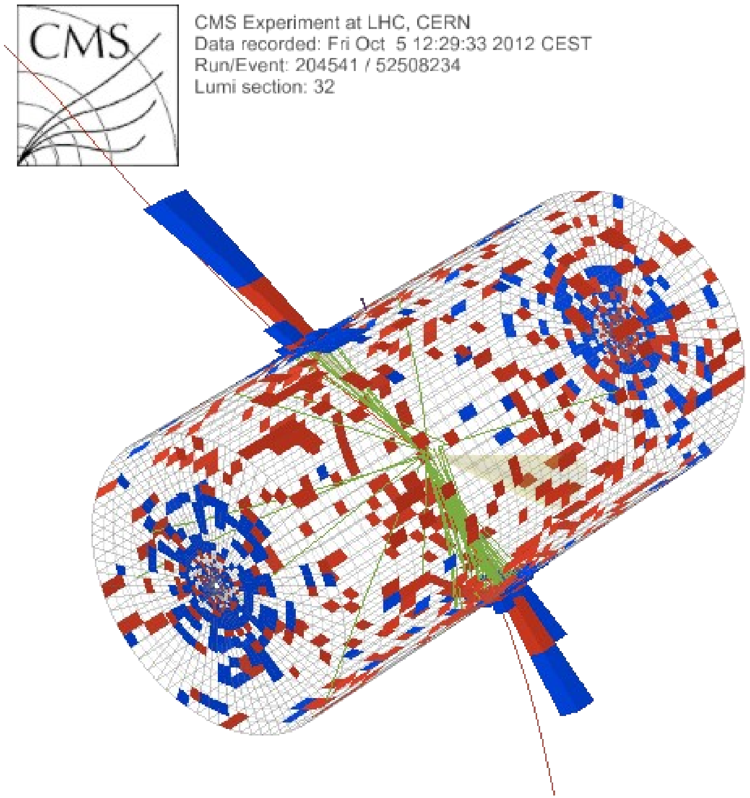
What is a jet?

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

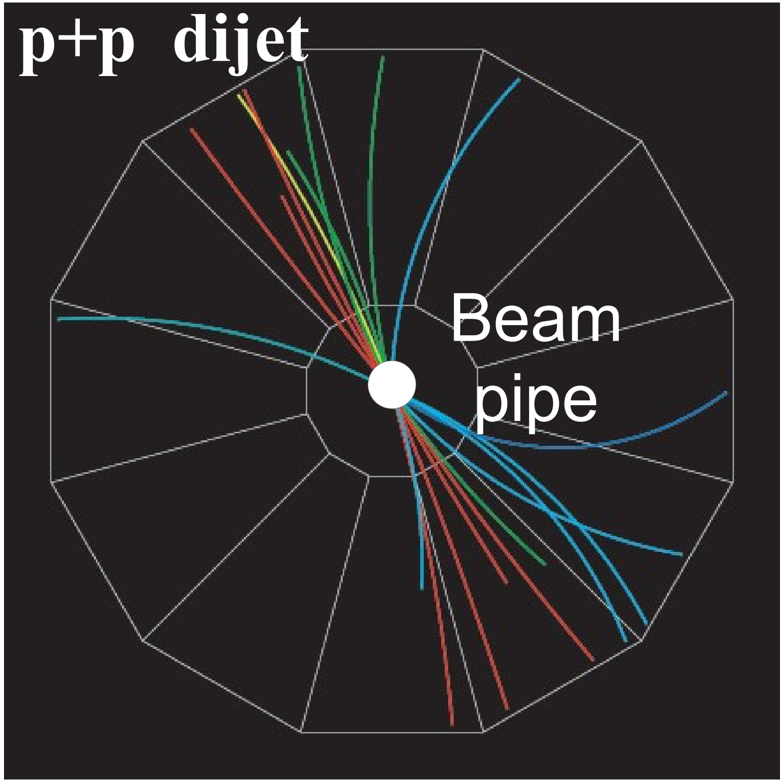
What is a jet?

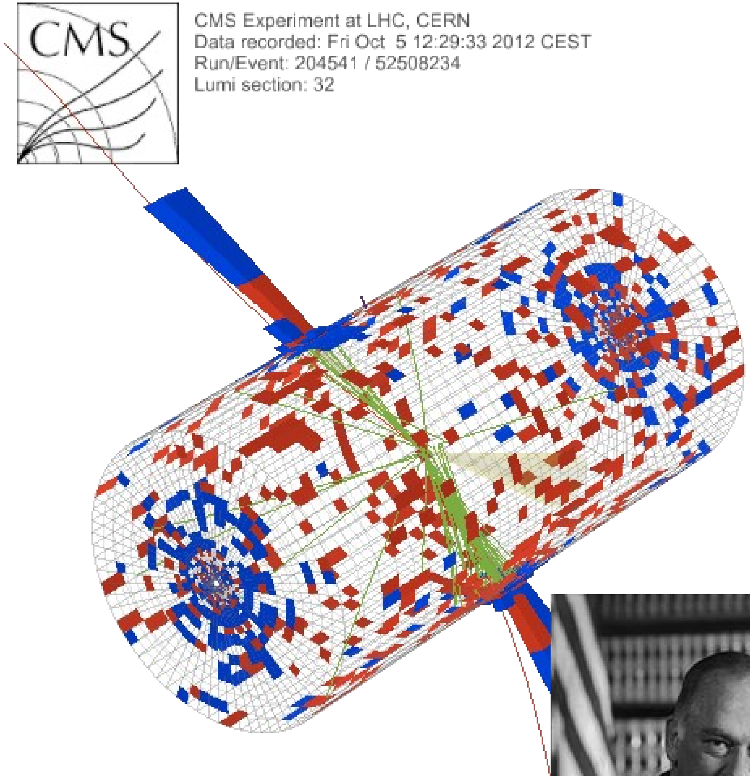
p+p dijet





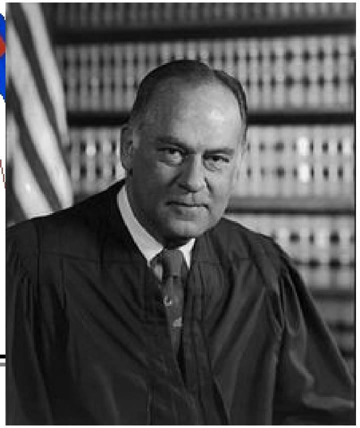
What is a jet?





"I know it when I see it"

US Supreme Court Justice Potter Stewart, Jacobellis v. Ohio



Jet finding algorithms

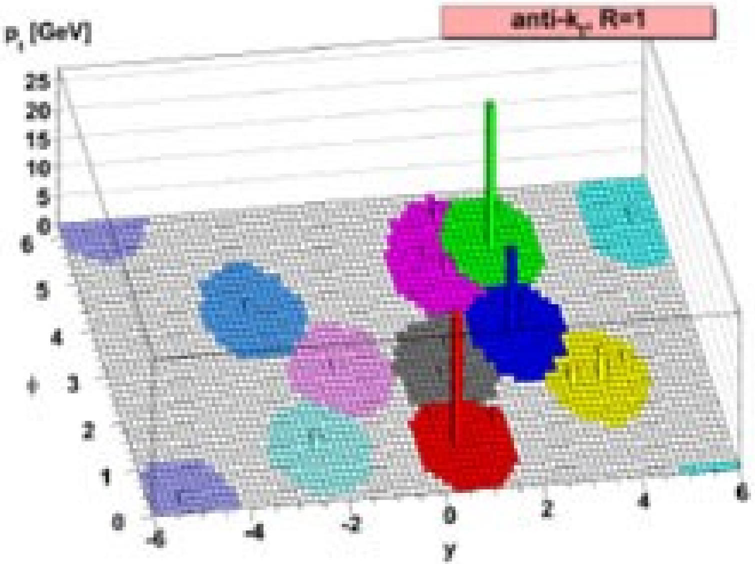
Tracks

Clusters

Particles

Jet finding algorithm

Jet candidates



- 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*

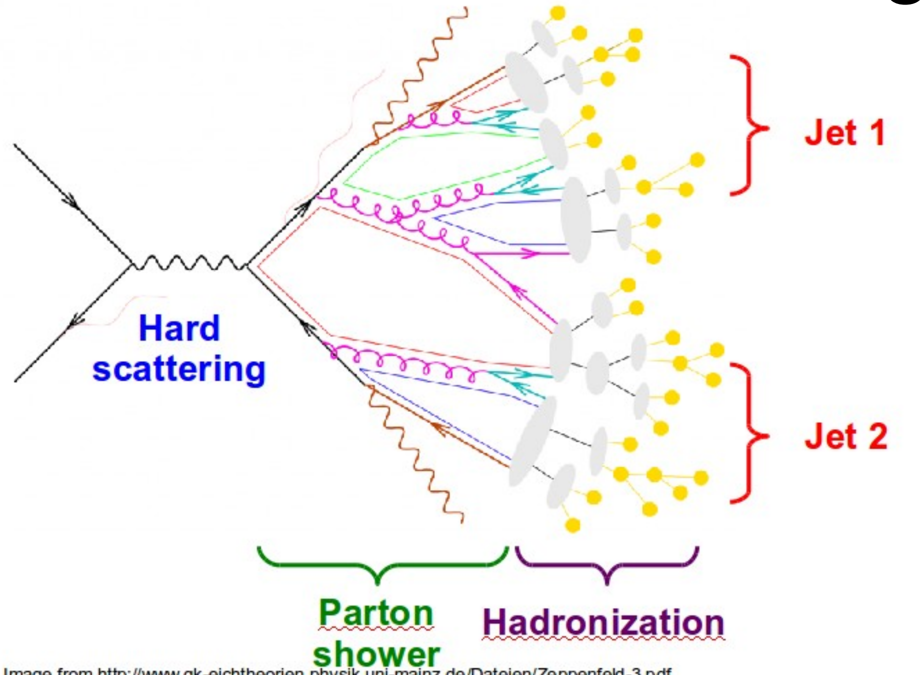


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- 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

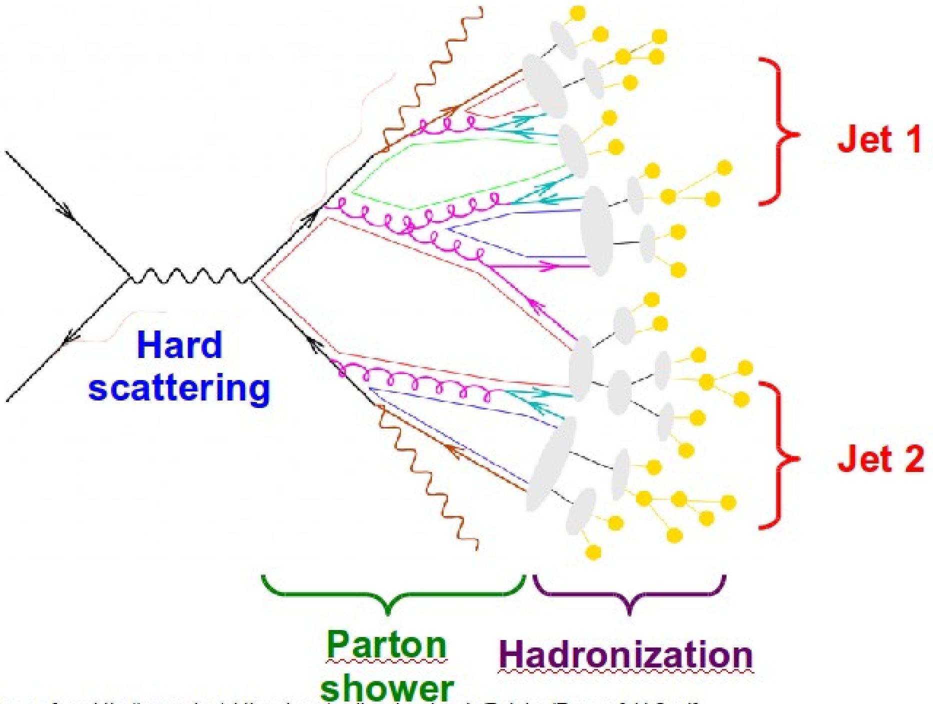
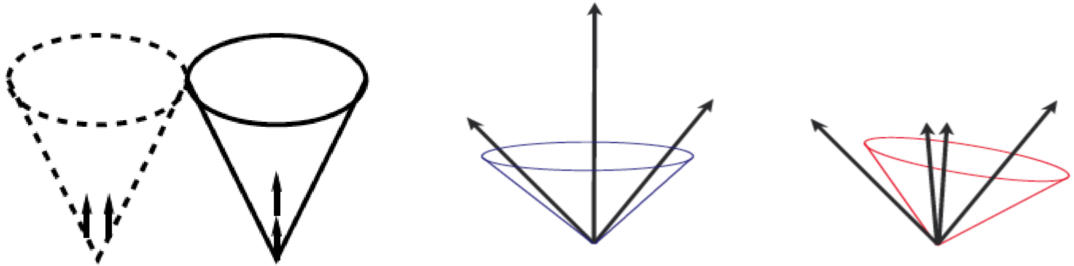
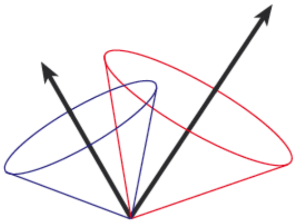


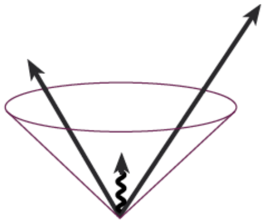
Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

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





OK



BAD: 2 jets are merged in one

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

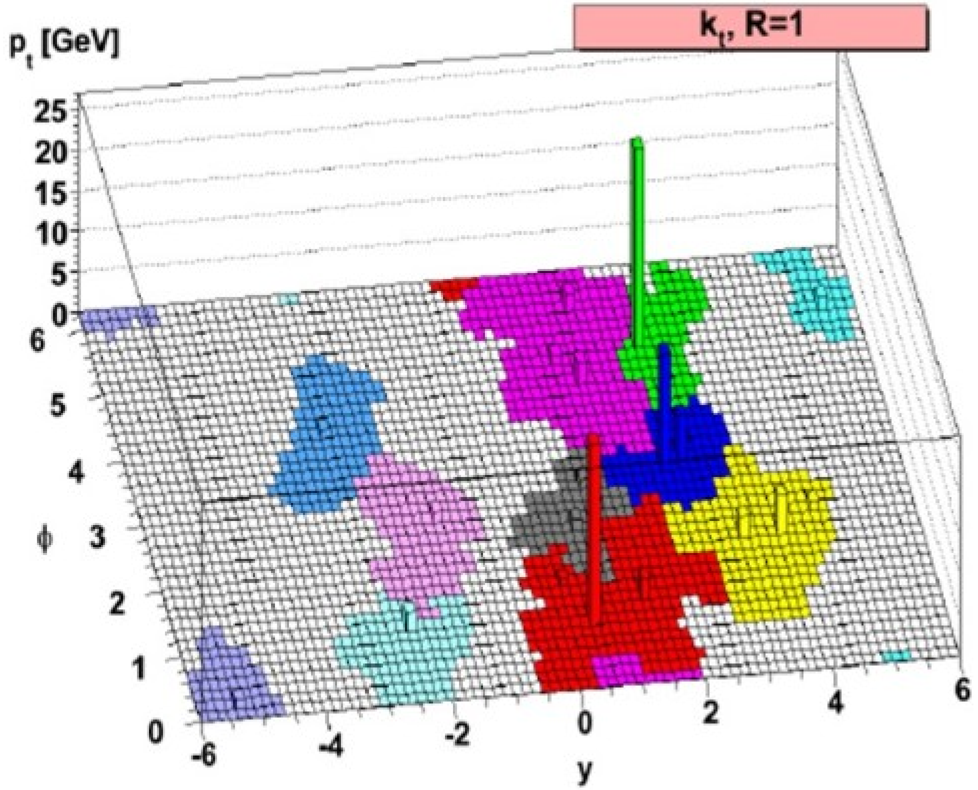
$$d_{ij} = min\boxed{\left(p_{T,i}^2, p_{T,j}^2\right)}\frac{\Delta R_{ij}^2}{R^2}$$

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

- 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

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

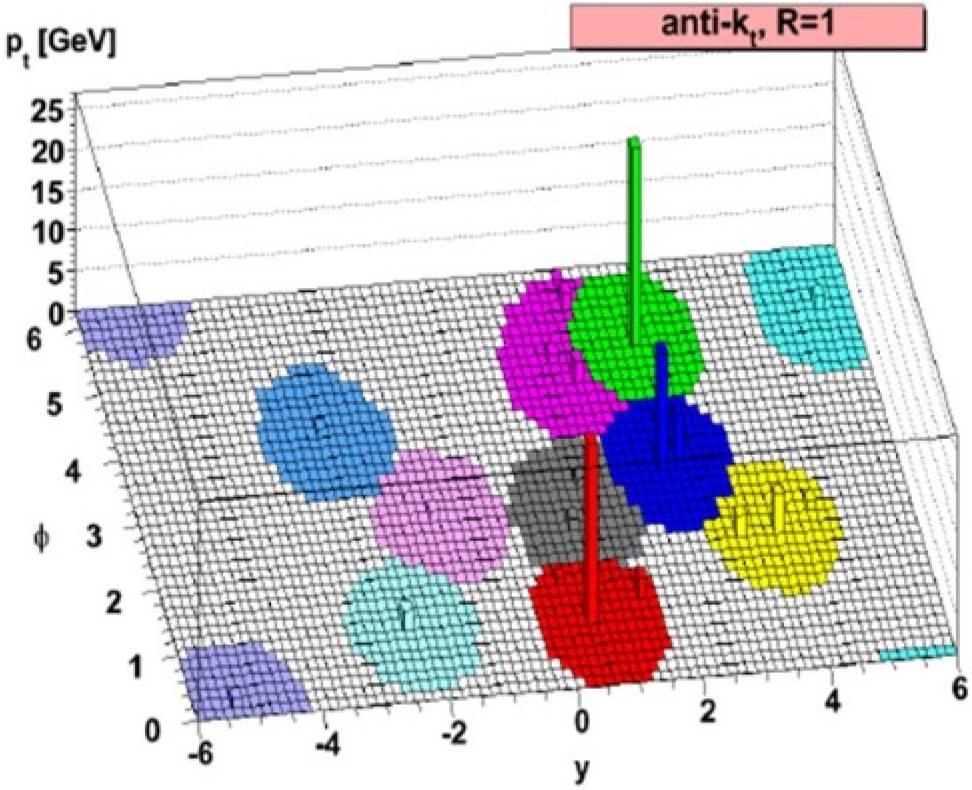
$$d_{iB} = p_{T,i}^{-2}$$

- 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

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

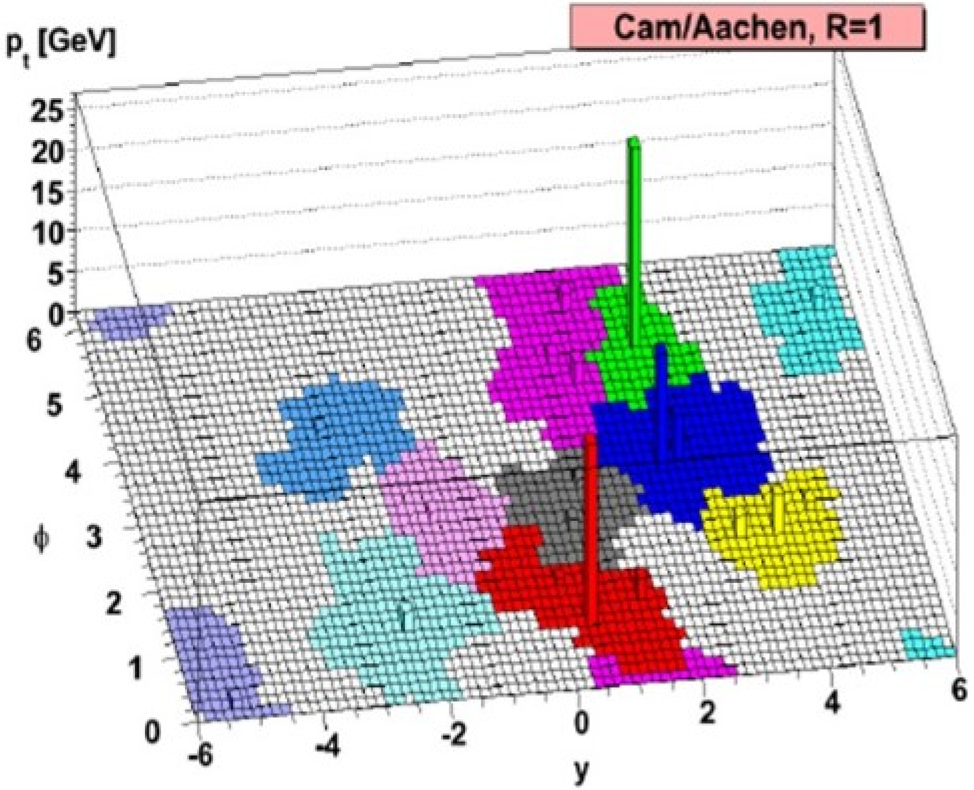
- For all *i,j* calculate:

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

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

Repeat until no particles left

Jet candidates

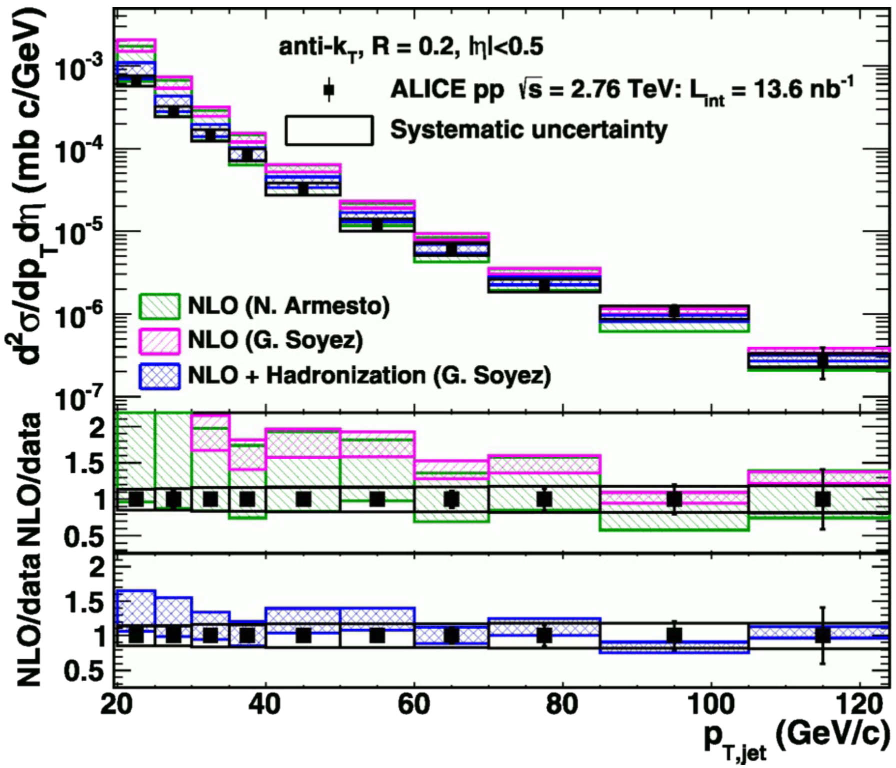


A jet is what a jet finder finds.

Jet cross-section in pp

√s = 2.76 TeV, R = 0.2 Inclusive

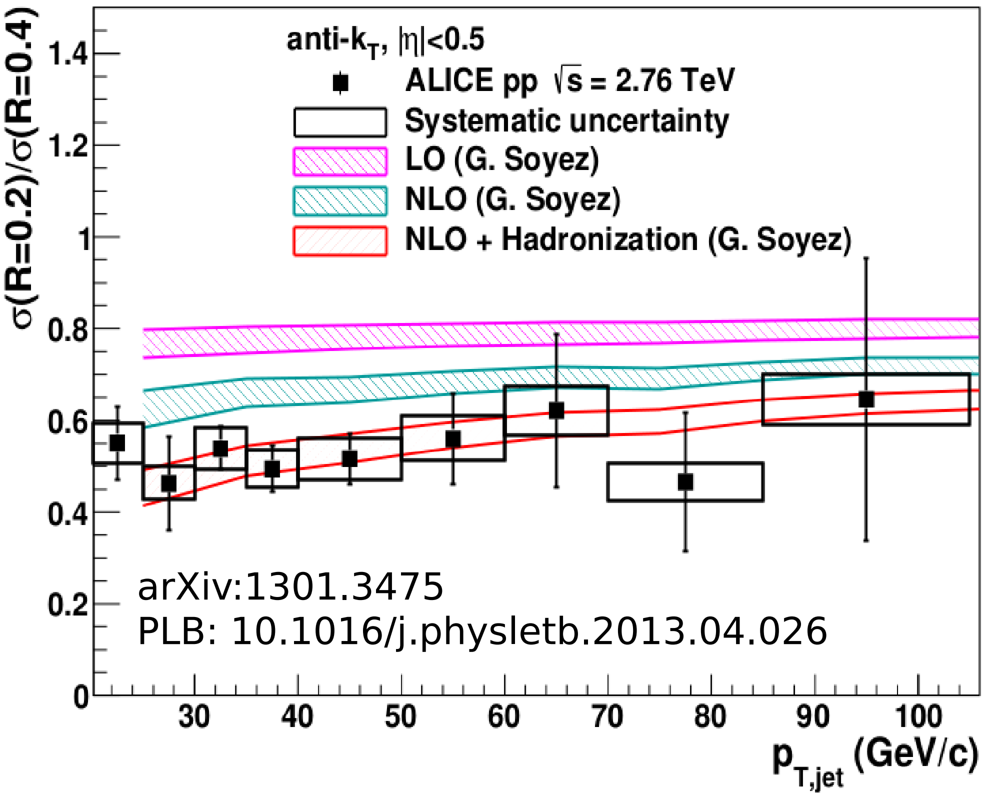
arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026

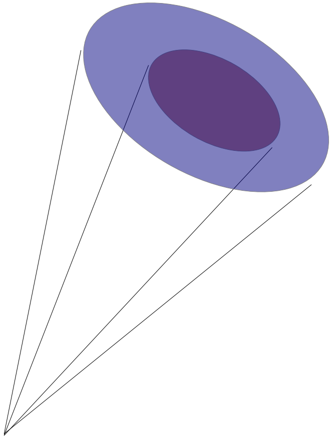


- Green and magenta bands: NLO on Parton level
- Blue band: NLO + hadronization
- Hadronization calculations necessary to describe data

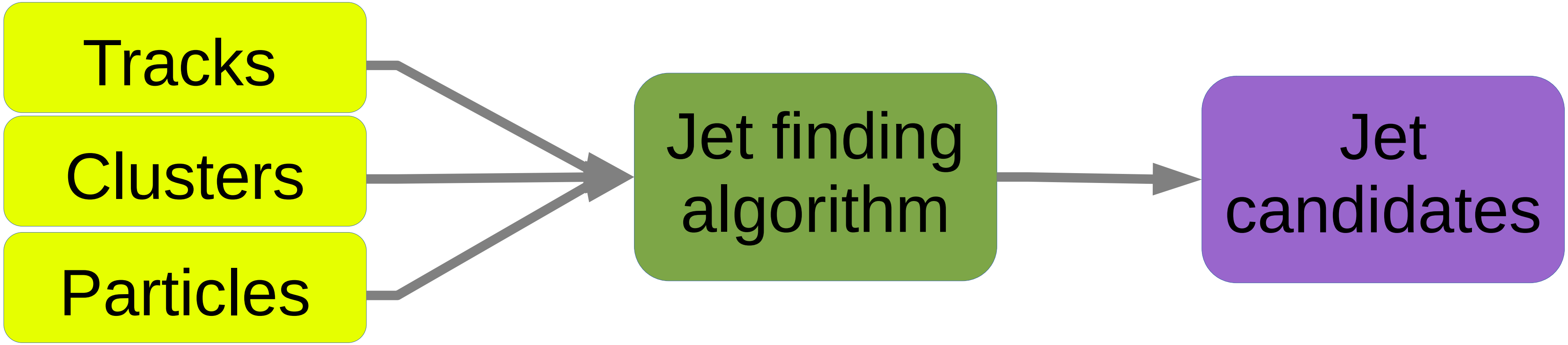
Jet ratios in pp

$\sqrt{s}$ = 2.76 TeV, R = 0.2, 0.4 Inclusive





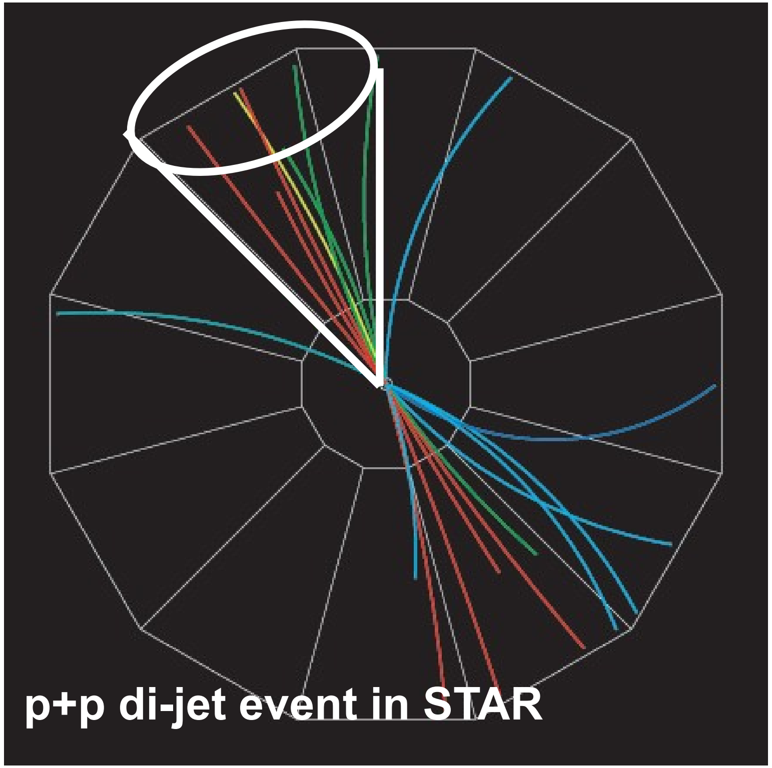
Mini-summary

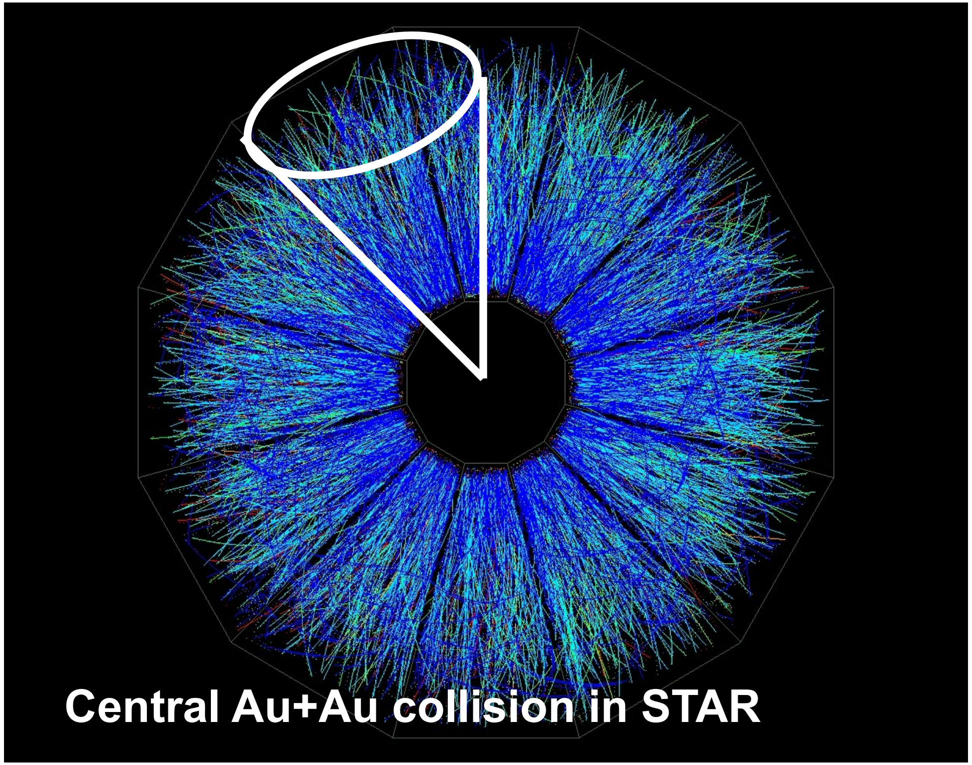


- Jets are not partons
- Good jet finders:
  - Infrared and colinear safe
  - k_T, anti-k_T, Cambridge/Aachen, SISCone
- Jet is defined by jet finder, its parameters
- PDFs, fragmentation functions non-perturbative
  → all jet measurements sensitive to somewhat non-perturbative effects
- Good agreement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

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

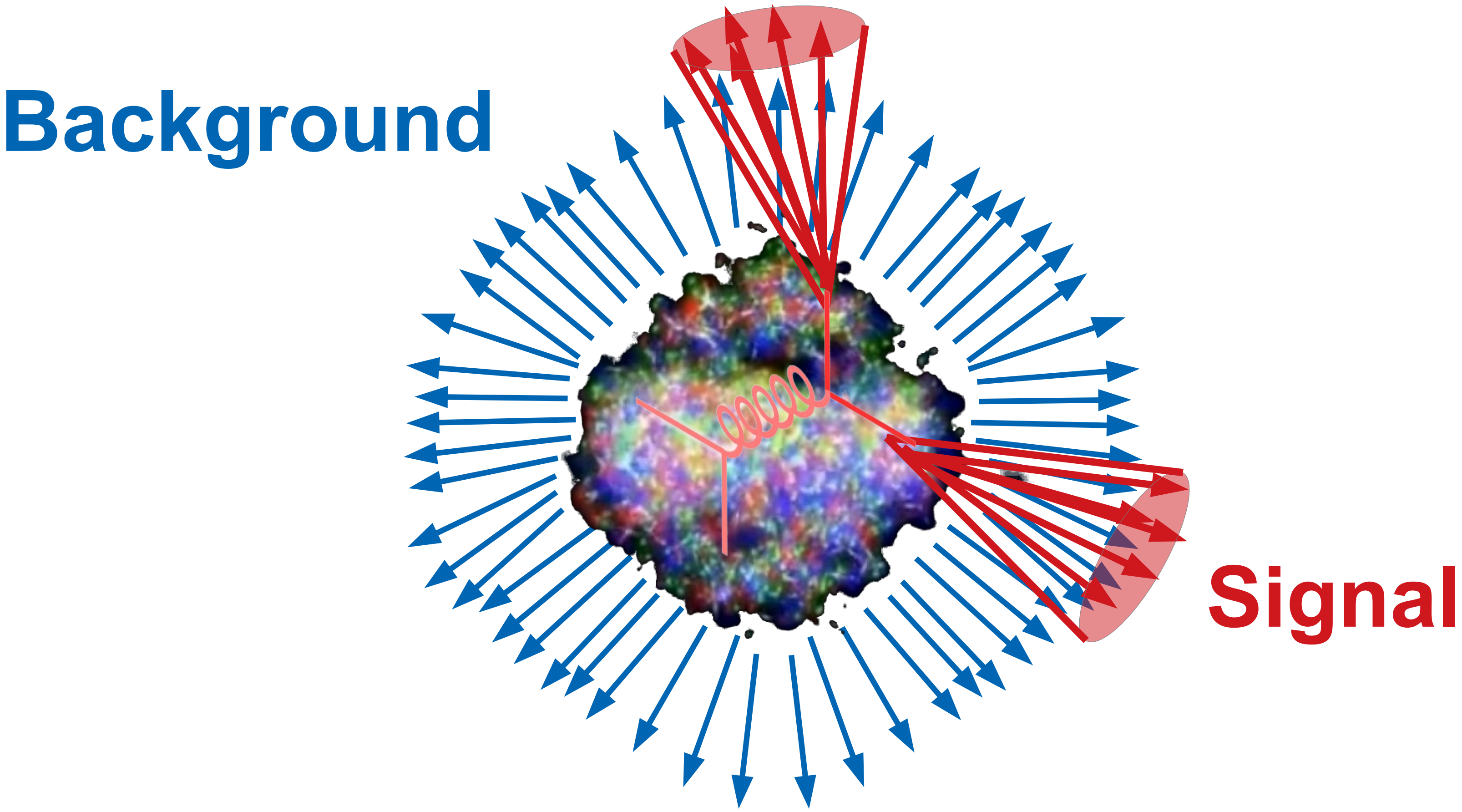
p+p vs A+A



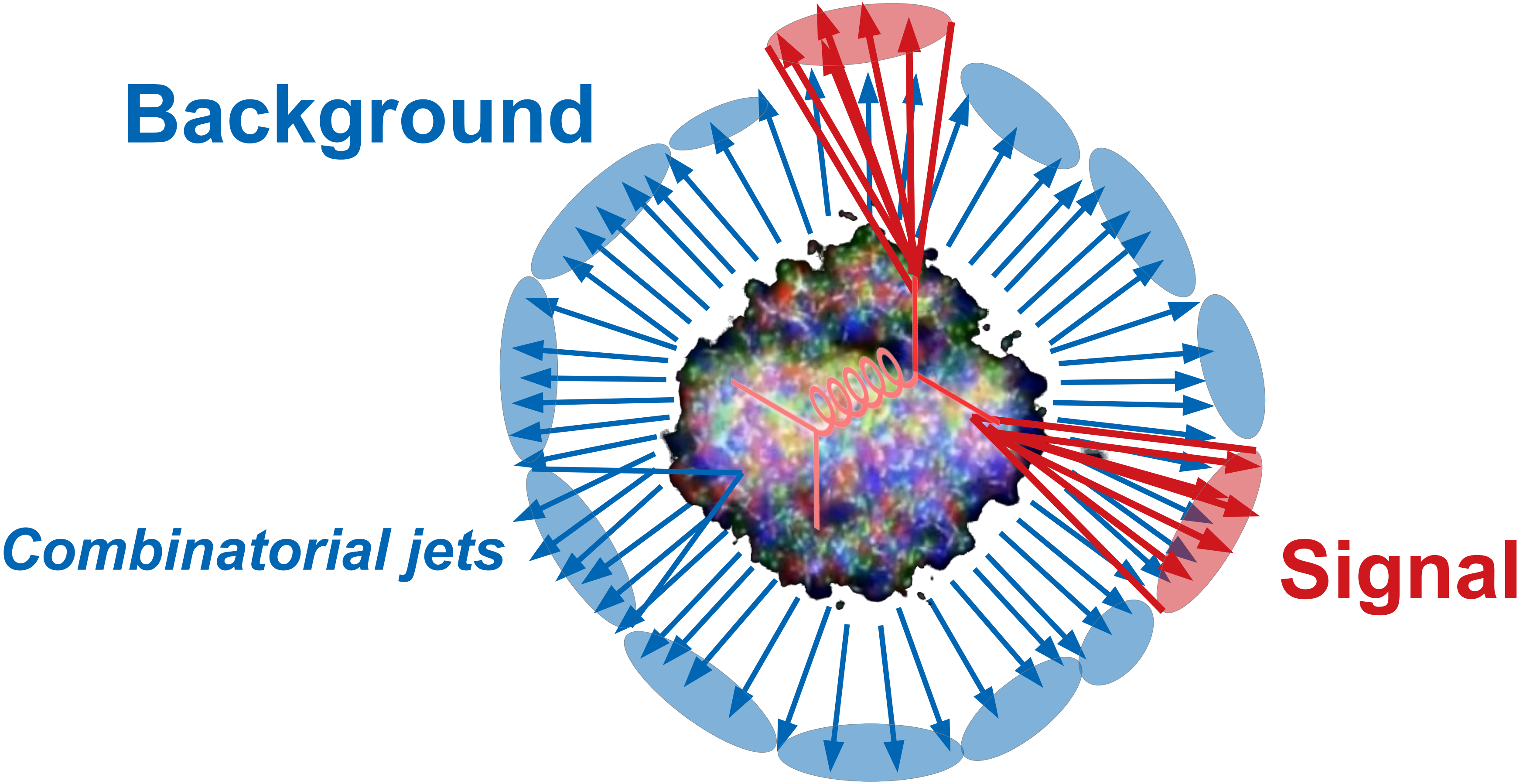


Signal vs Background:

The standard paradigm



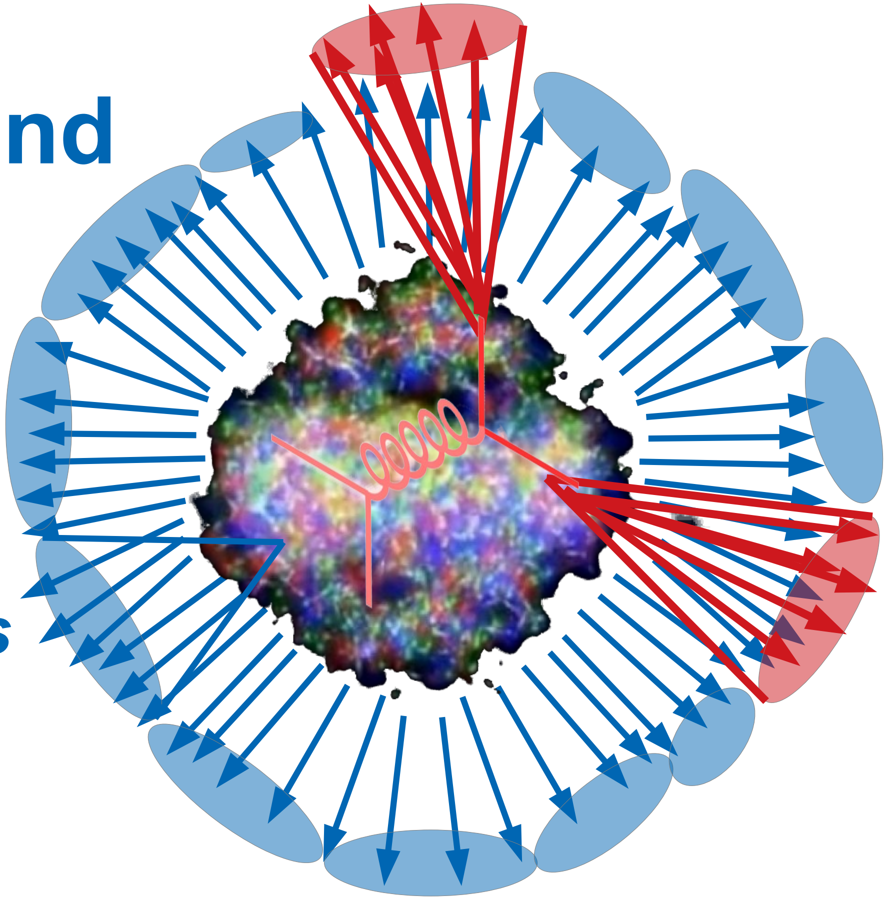
Signal vs Background:
The standard paradigm



Signal vs Background:

The standard paradigm

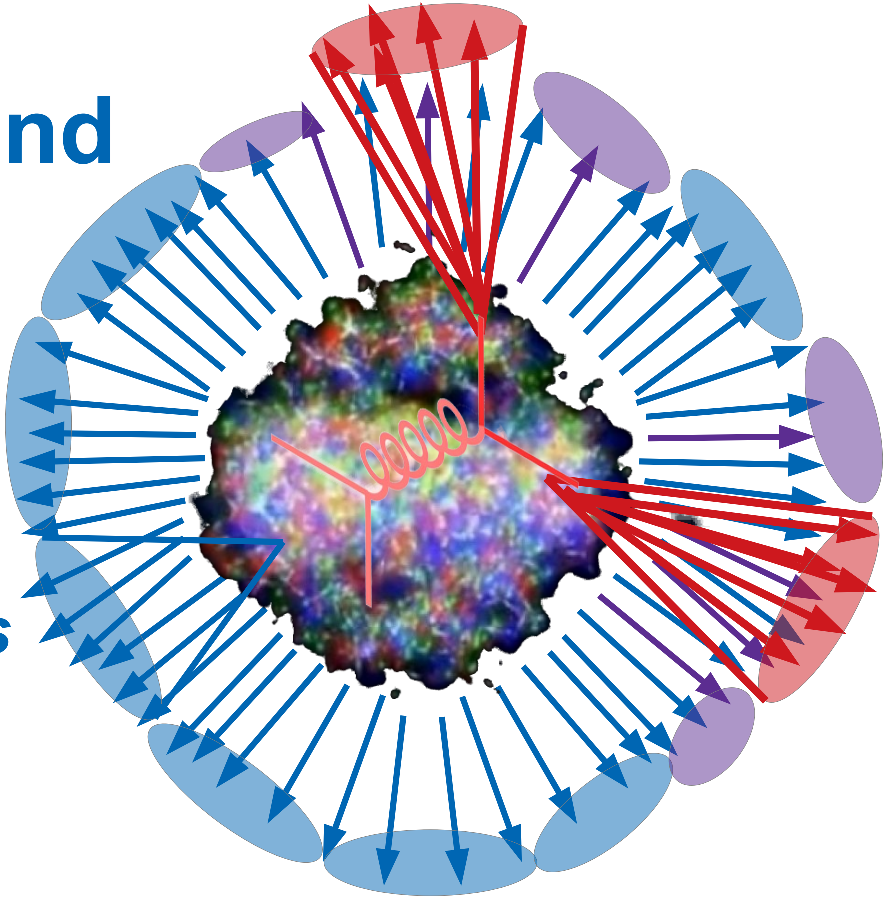
Background



Combinatorial jets = “fake” jets

Signal

Signal vs Background:
The standard paradigm



*Some gray areas

Jet finding in AA collisions

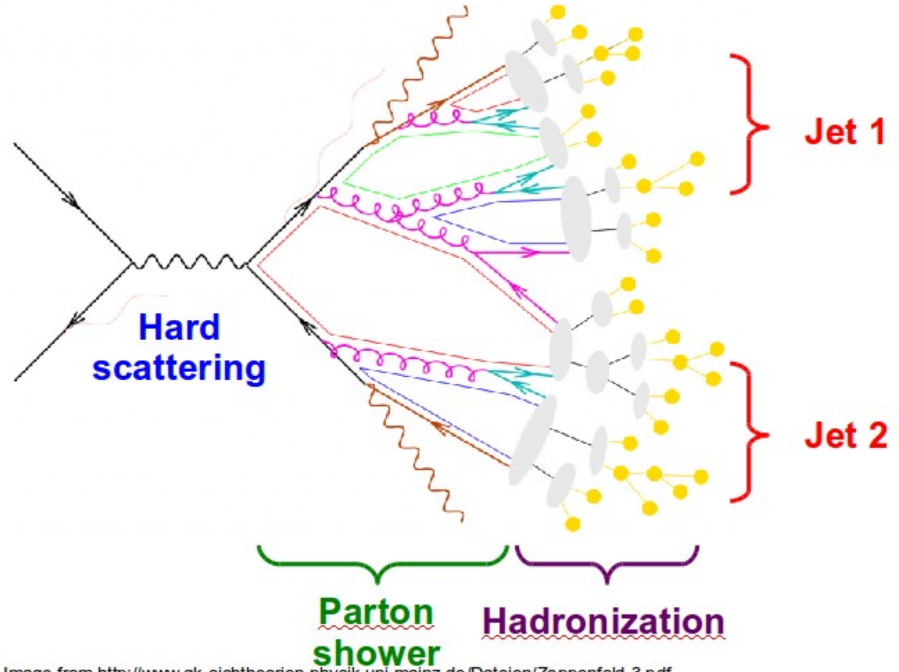
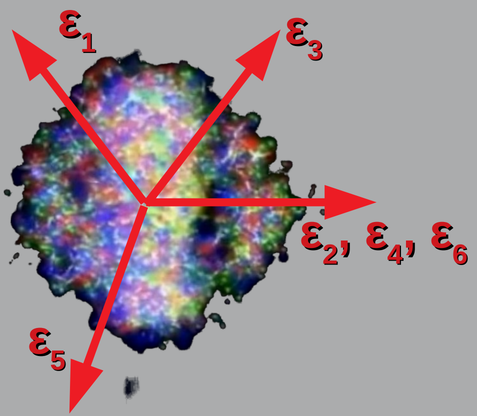


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- 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

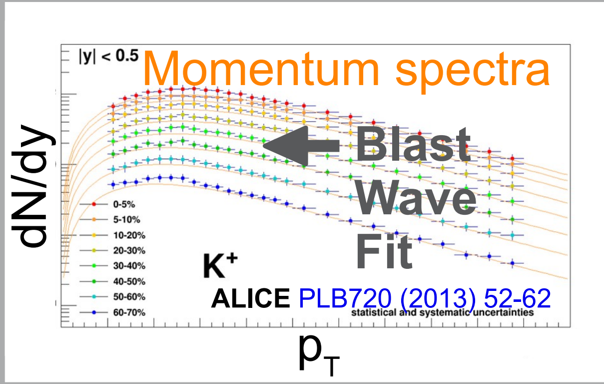
Event properties



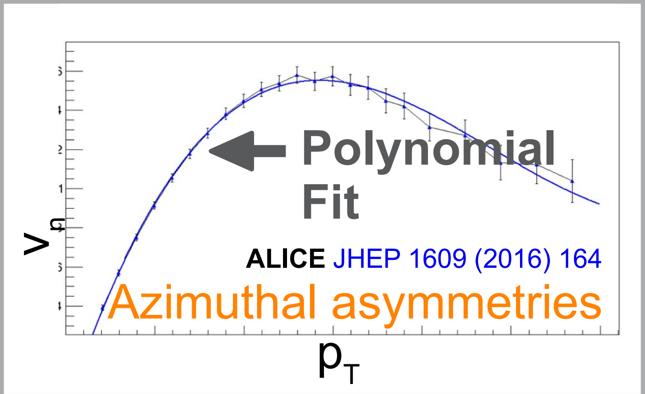
- Even event planes fixed at Ψ=0
- Odd planes at random φ
- Multiplies from ALICE PRC88 (2013) 044910

No jets! No resonances
Emulates hydro correlations

Track properties



→ Random p_T

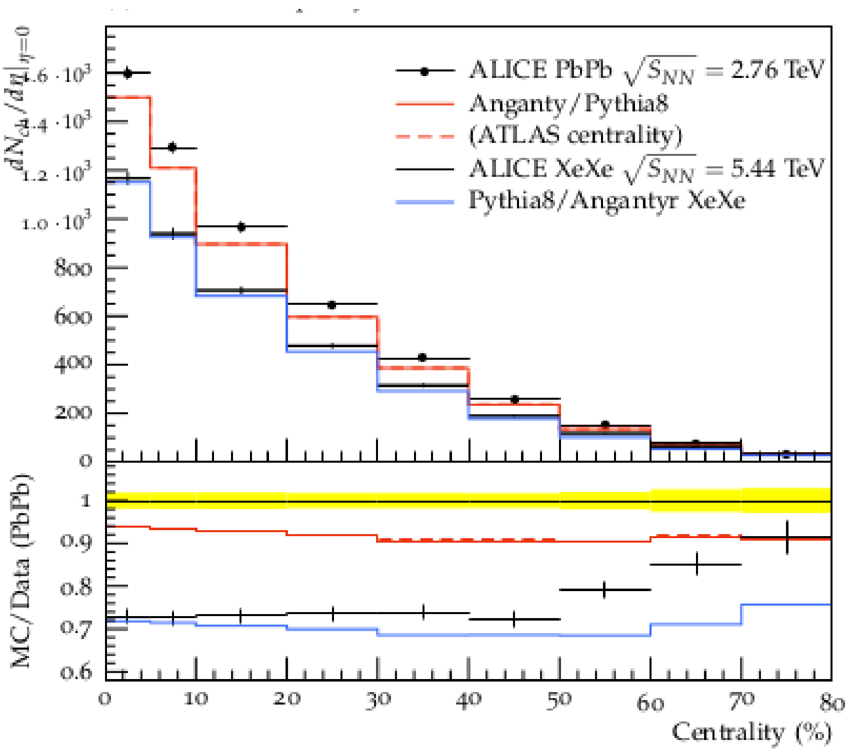


→ v_n → Random φ

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

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

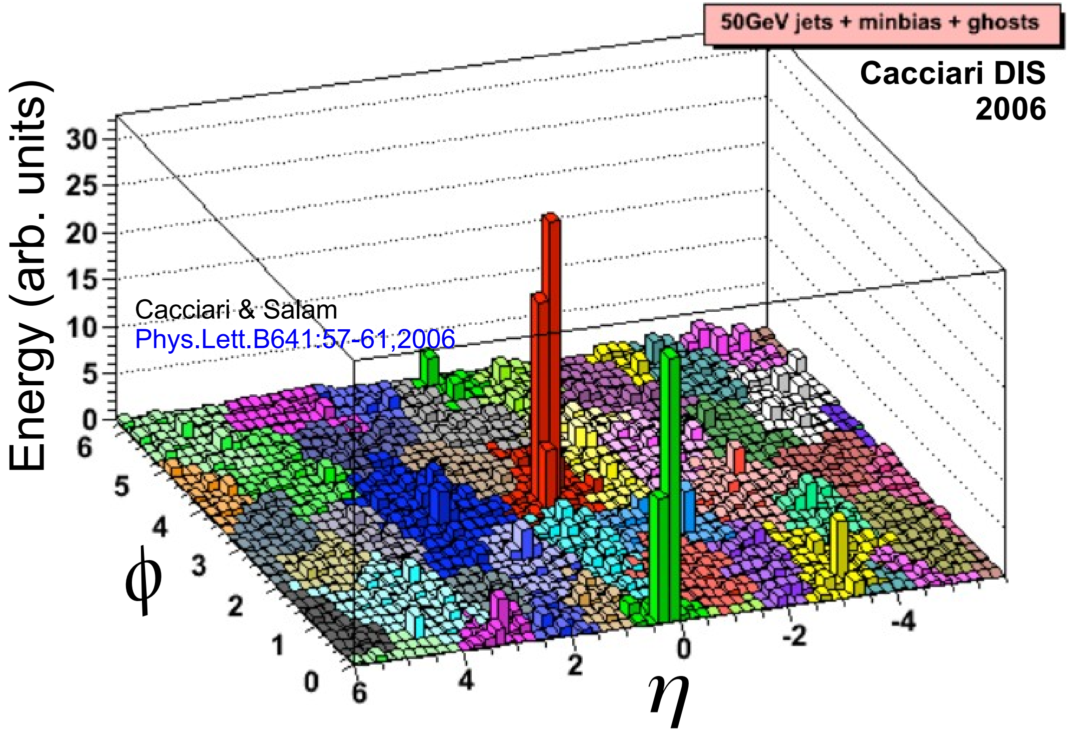
- For all *i,j* calculate:
  $$d_{ij} = min(p_{T,i}^2, p_{T,j}^2) \Delta R_{ij}^2$$
  $$d_{iB} = p_{T,i}$$
- Combine smallest d_{ij}.
  If d_{iB} smallest, $d_{iB} \rightarrow$ jet

Repeat until no particles left

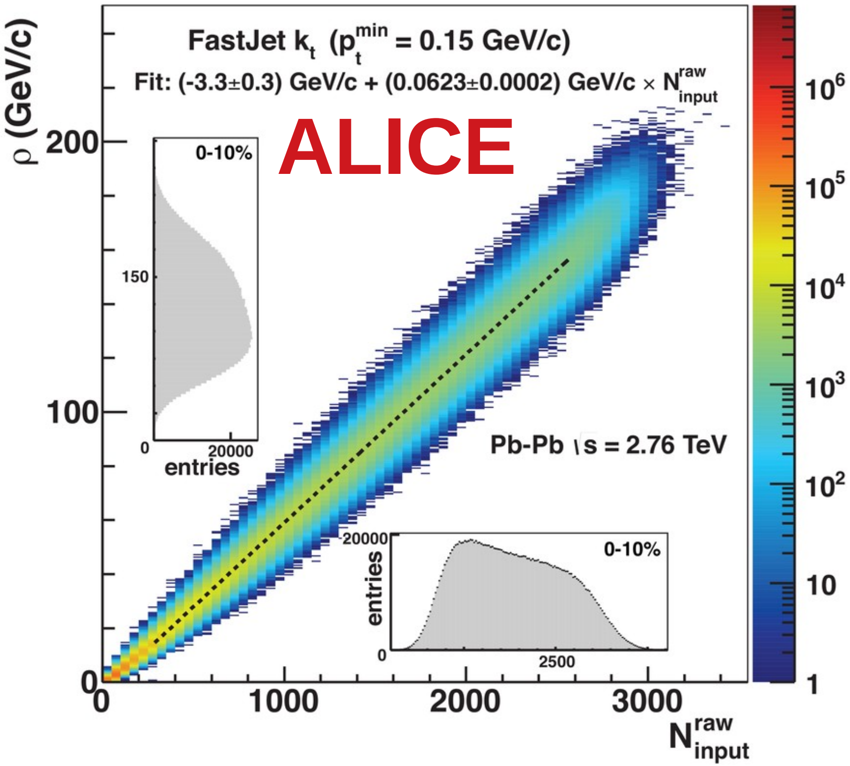
Jet candidates

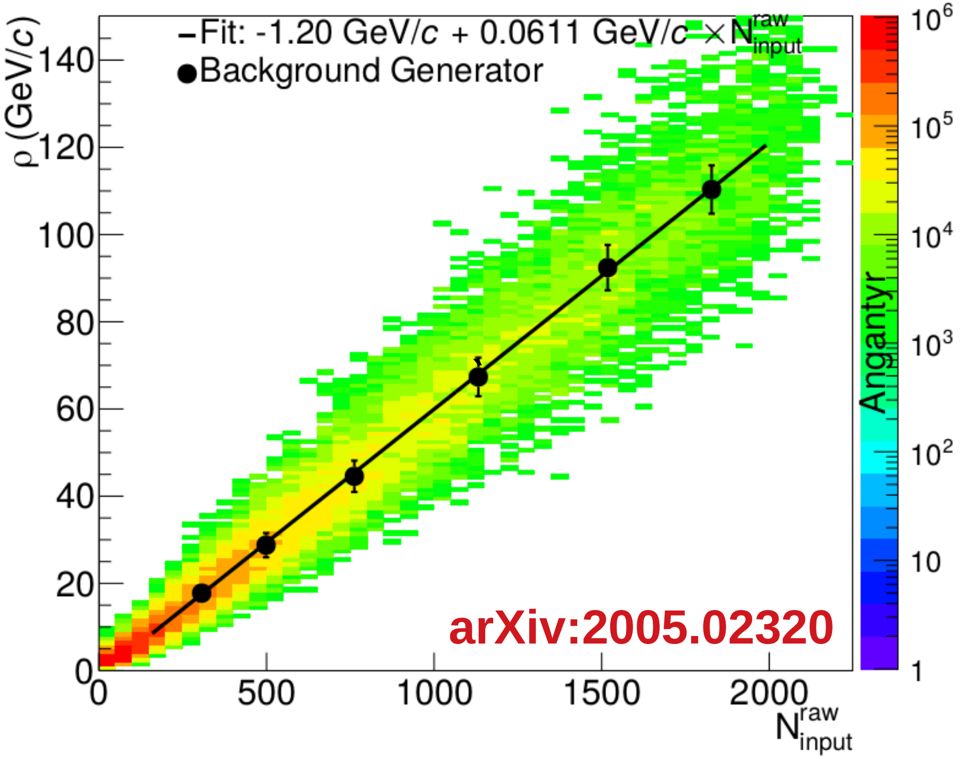
Median $\rho = p_T/A$

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

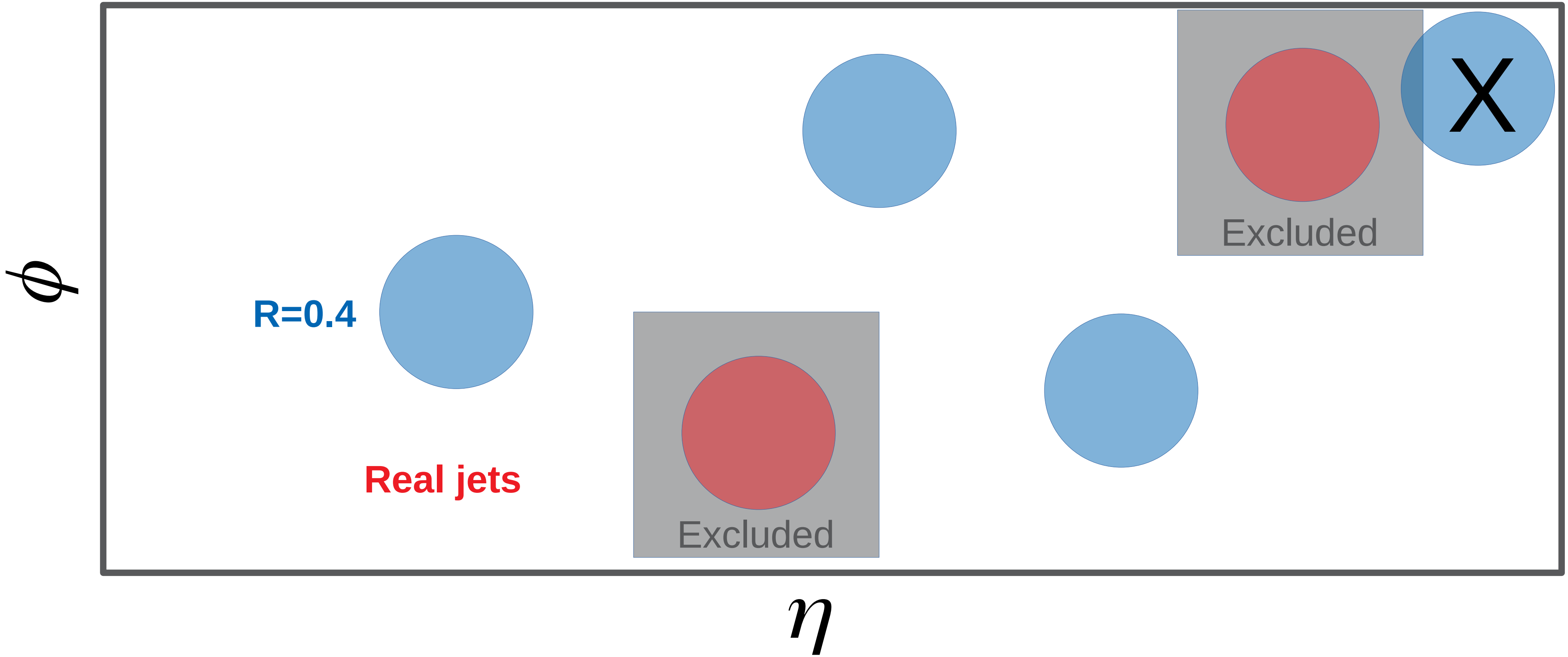


Background density ρ





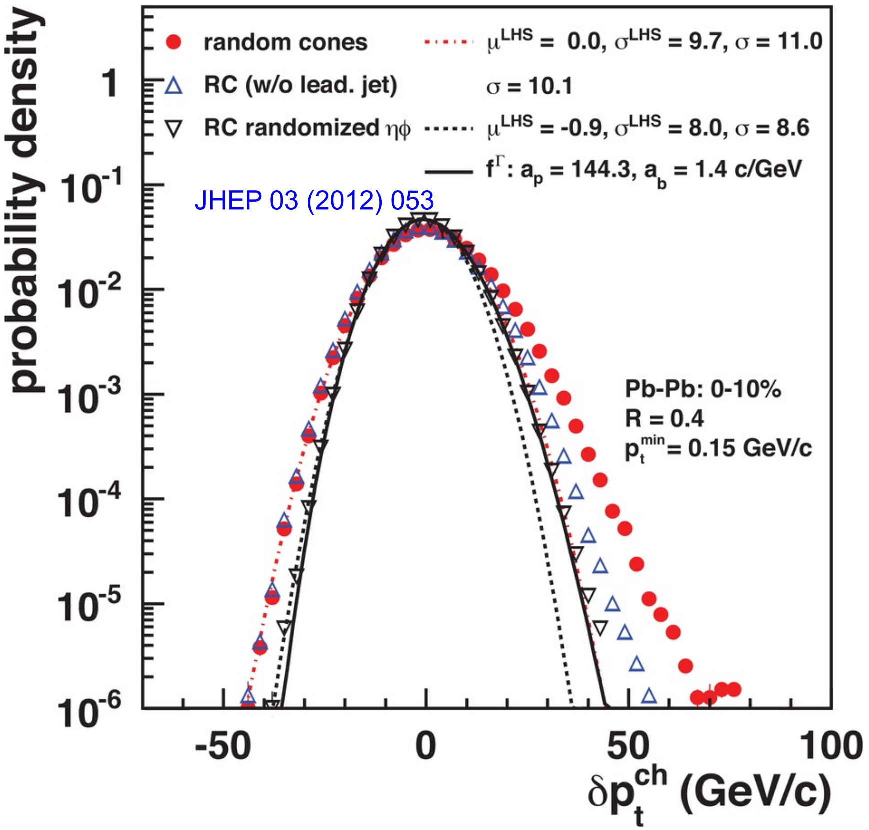
Random cones



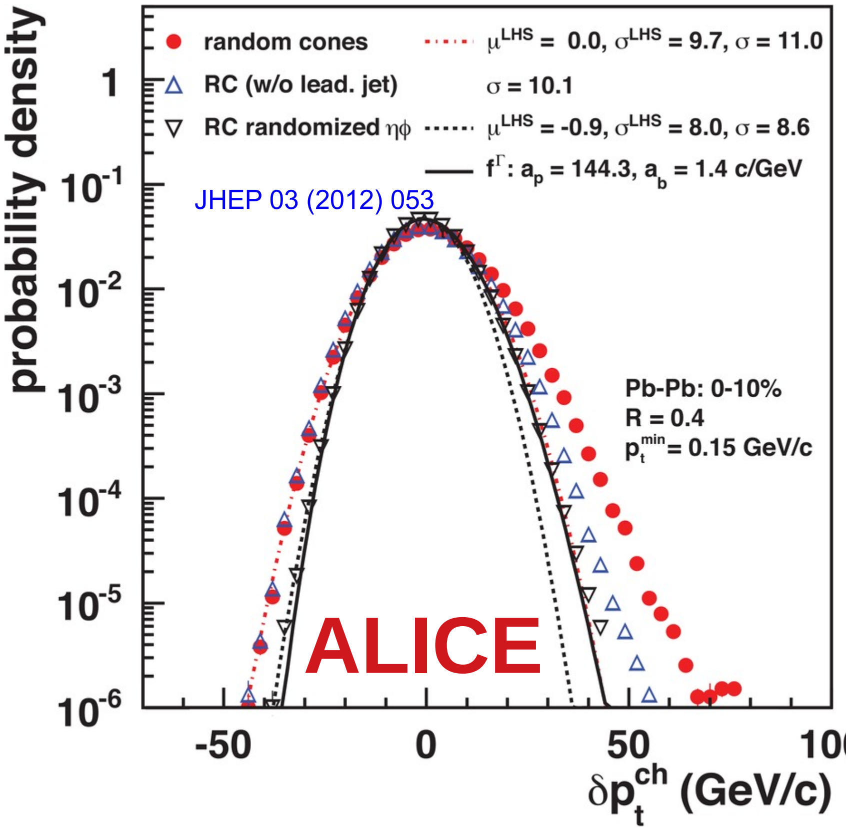
Random cones in ALICE

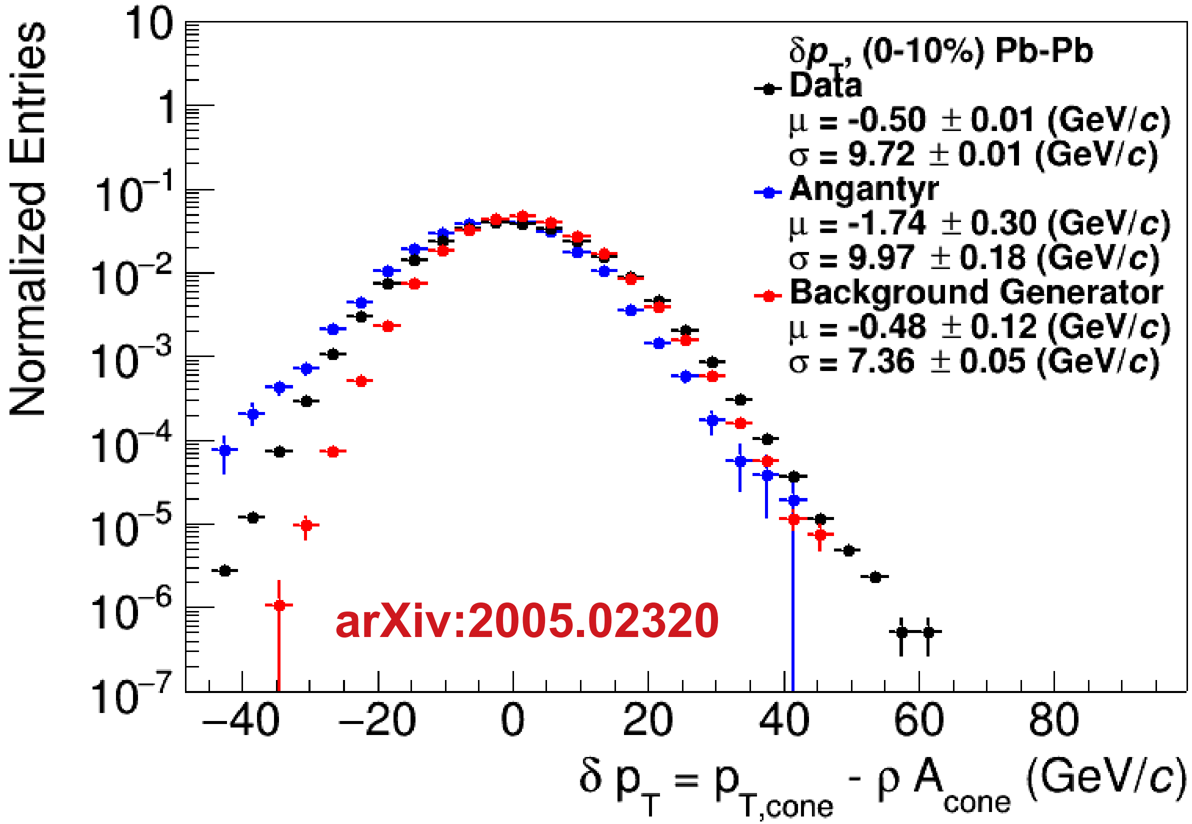
- Estimate ρ
  - k_T jet finder → jet candidates
  - ρ = Median(p_T/A)
- Draw Random cone

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



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:

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

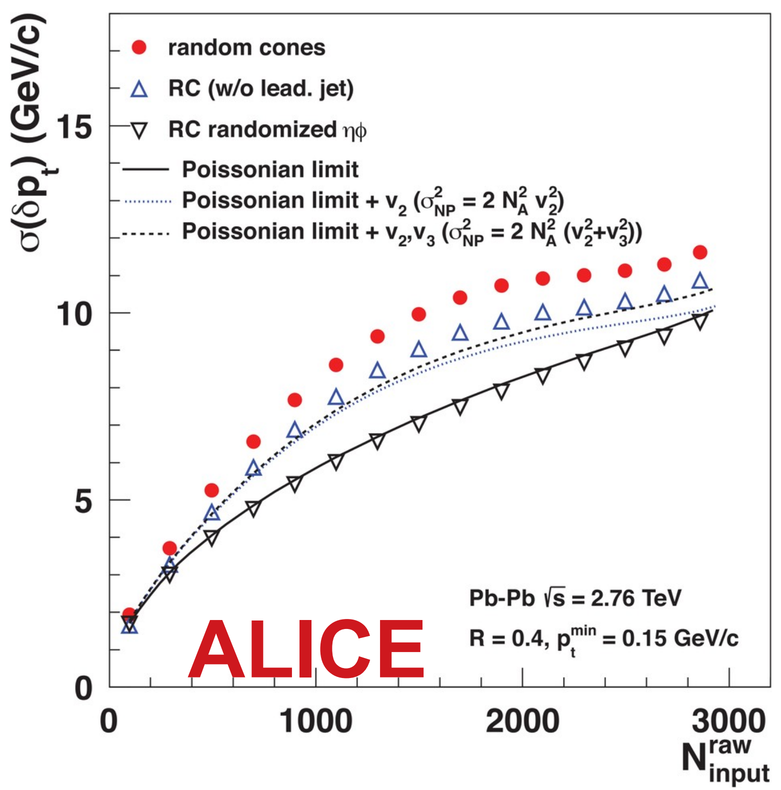
$$N=\frac{N_{total}}{A_{total}}\pi R^2 \qquad \mu_{total}=\frac{Np}{b}=N\,\mu_{p_T},\ \sigma_{total}=\frac{\sqrt{Np}}{b}=\sqrt{N}\,\sigma_{p_T}$$

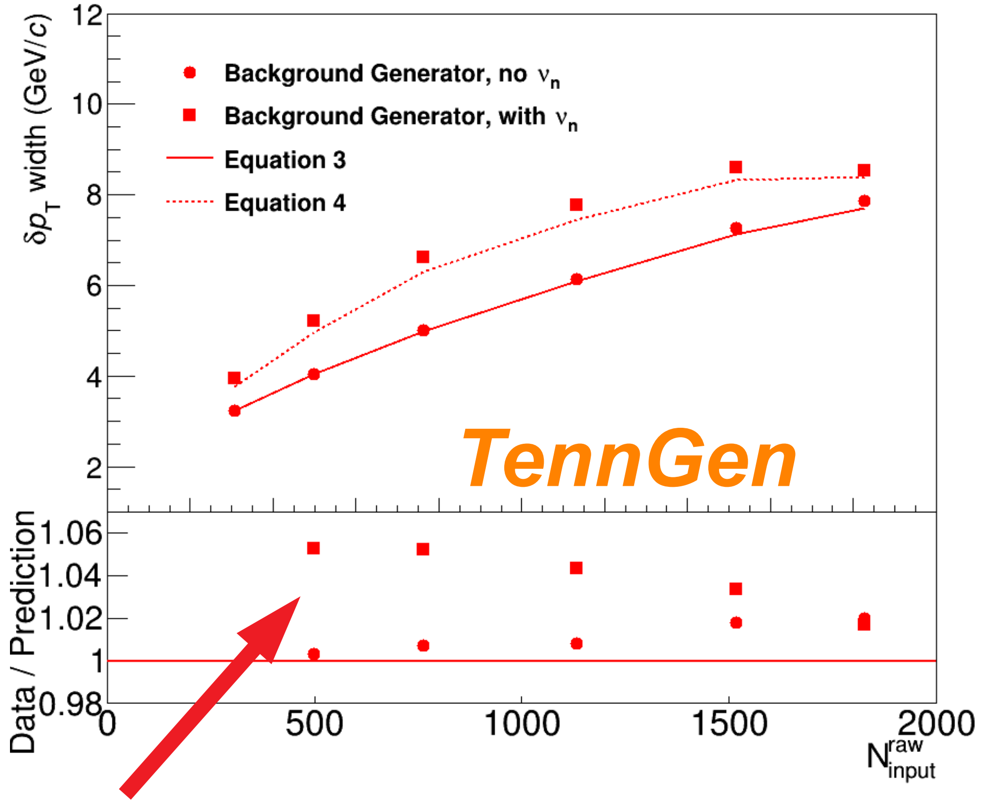
Add Poissonian fluctuations in N: $\sigma_{total}=\sqrt{N\,\sigma_{p_T}^2+N\,\mu_{p_T}^2}$

Add non-Poissonian fluctuations in N due to flow

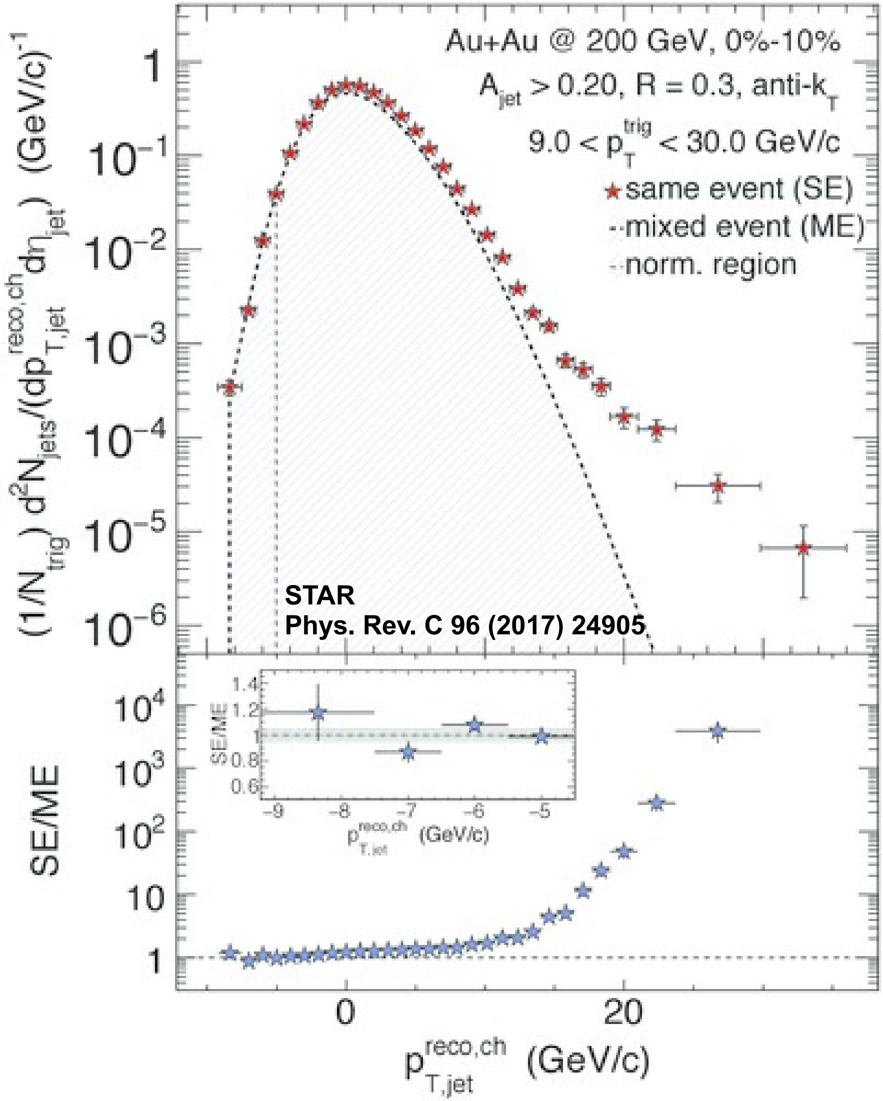
$$\sigma_{total}=\sqrt{N\,\sigma_{p_T}^2+\left(N+2\sum_n v_n^2\right)\mu_{p_T}^2}$$

Width vs multiplicity





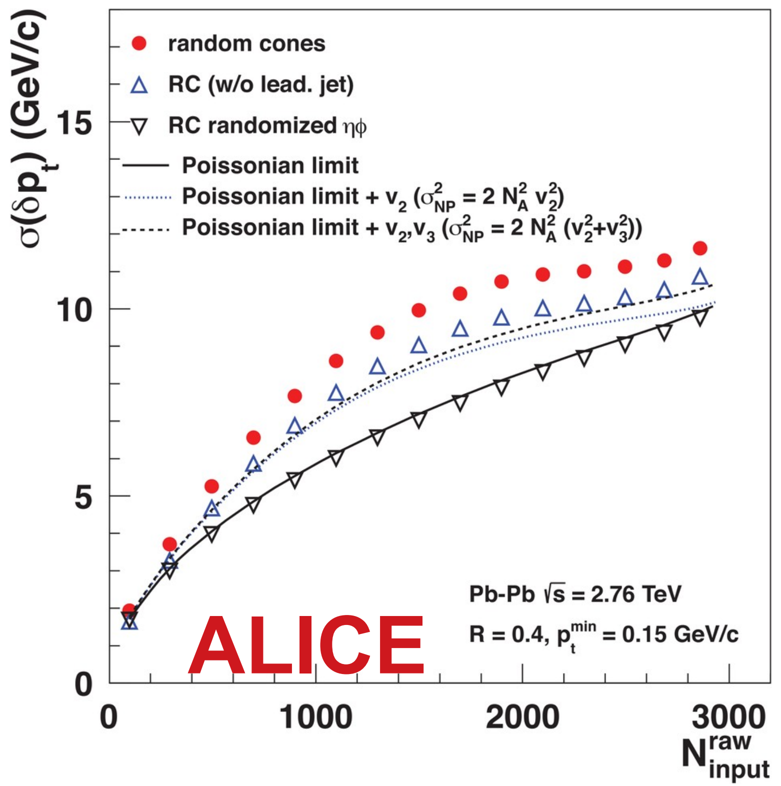
Small deviations

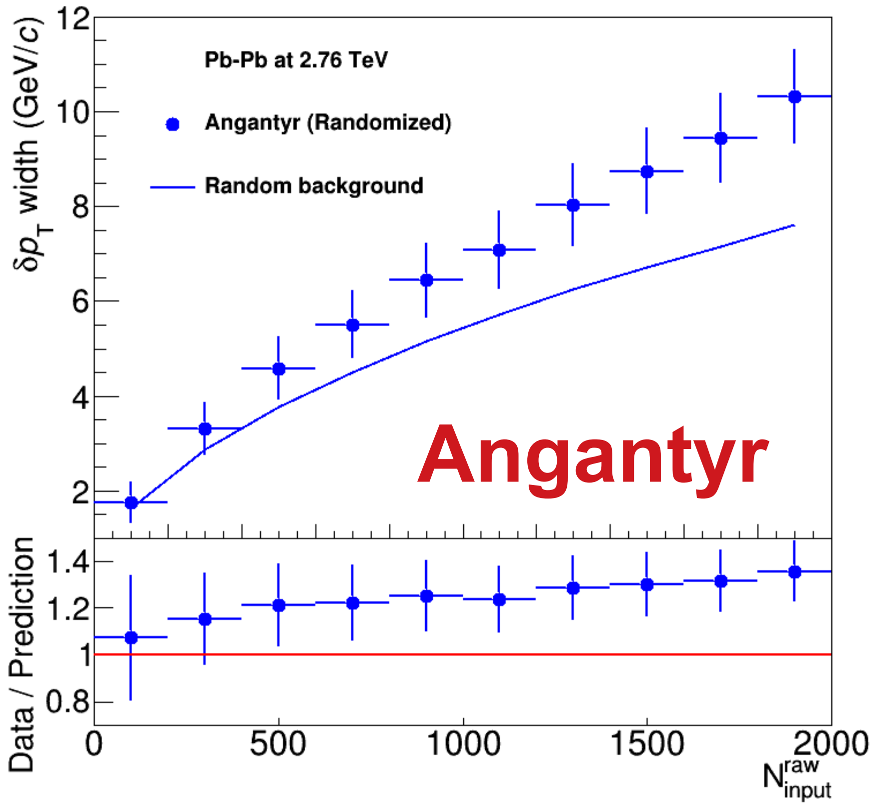


Mixed events

- 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

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

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

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

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

Assumes shape

Σp_T of N particles → N-fold convolution:

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

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

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

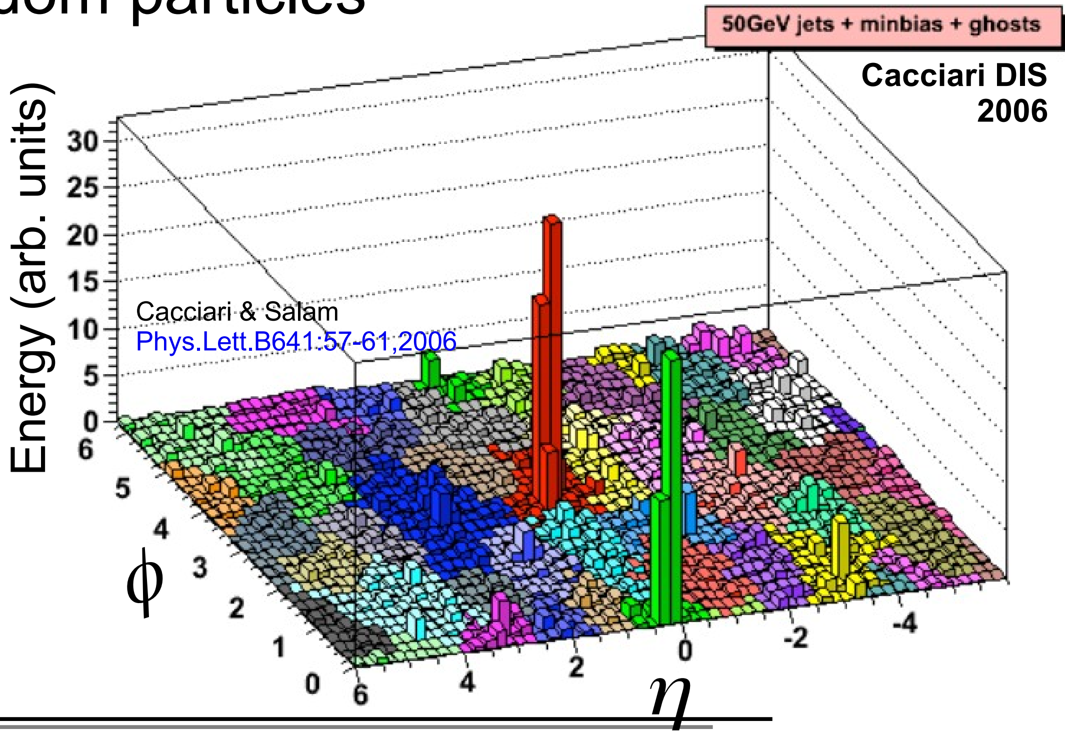
Add non-Poissonian fluctuations in N due to flow

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

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

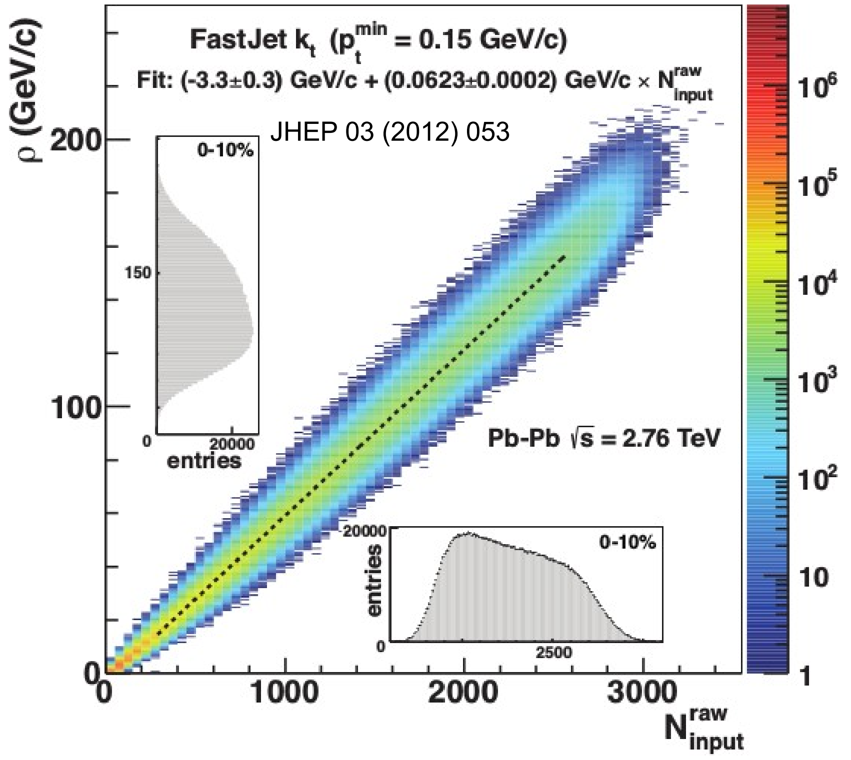


Jets in A+A collisions: Dealing with background

Focus on smaller angles

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

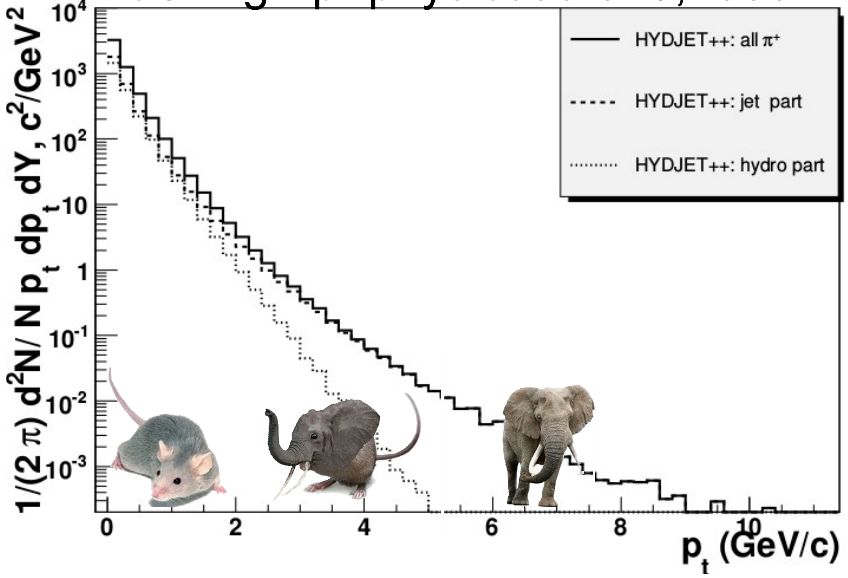
Aside: "quark" and "gluon" jet only defined at leading order.



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

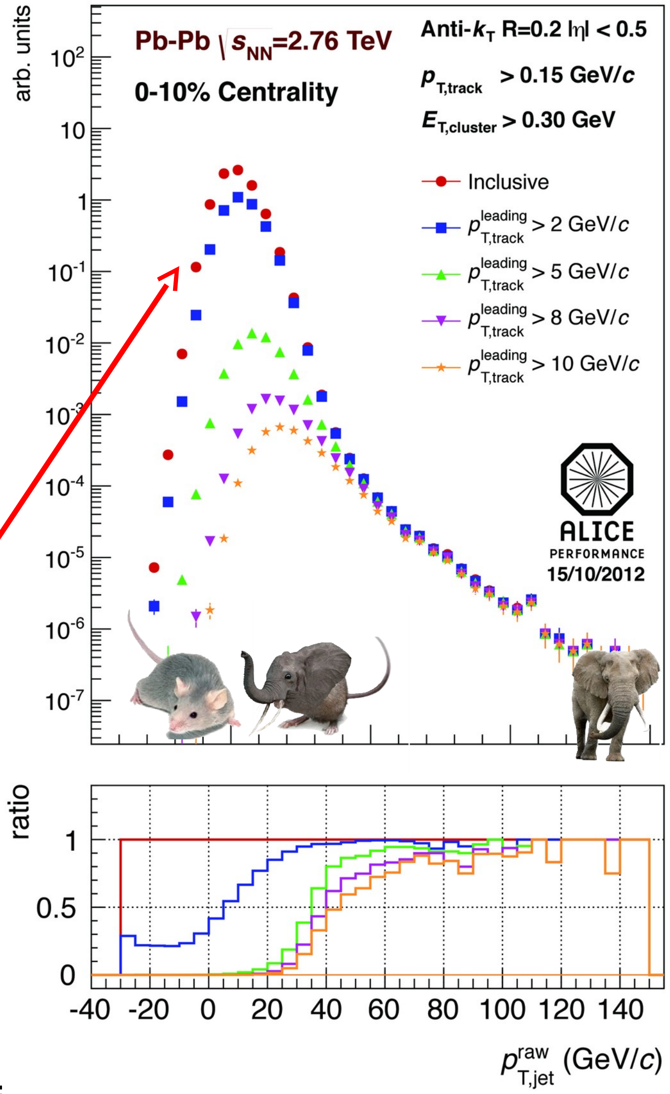


"Quark" and "gluon" jets only defined at leading order!

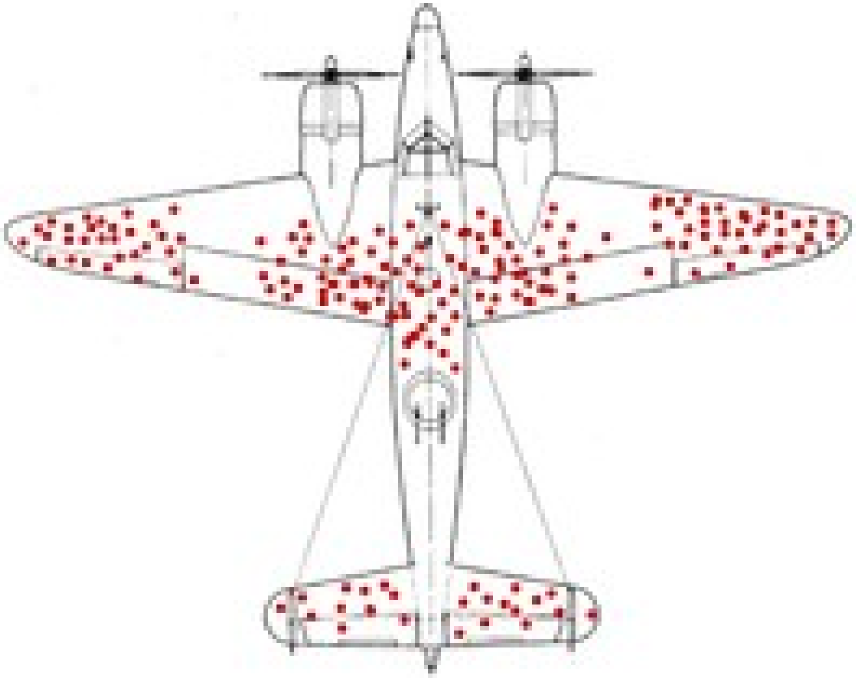
Area-based subtraction

- 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/

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

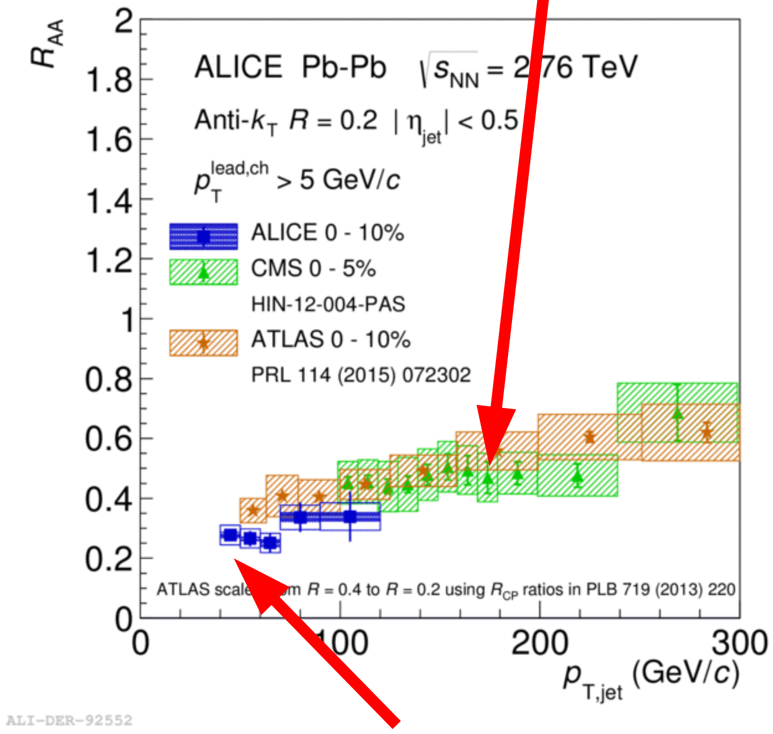
Bias & background

- **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**

Iterative procedure

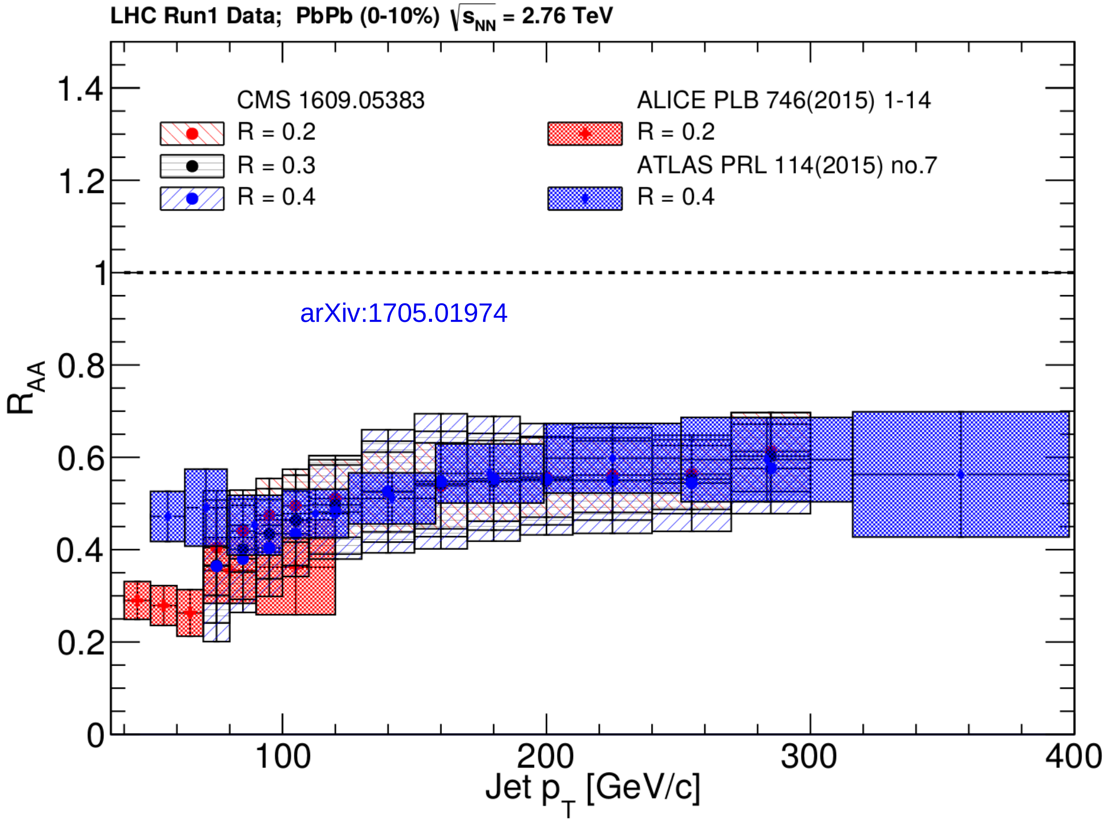
- Used by ATLAS & CMS
- ATLAS
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with
    $E_{tower} > \langle E_{tower} \rangle$
    Track jets: Use tracks with p_T>4 GeV/c
  - Calorimeter jets from above 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



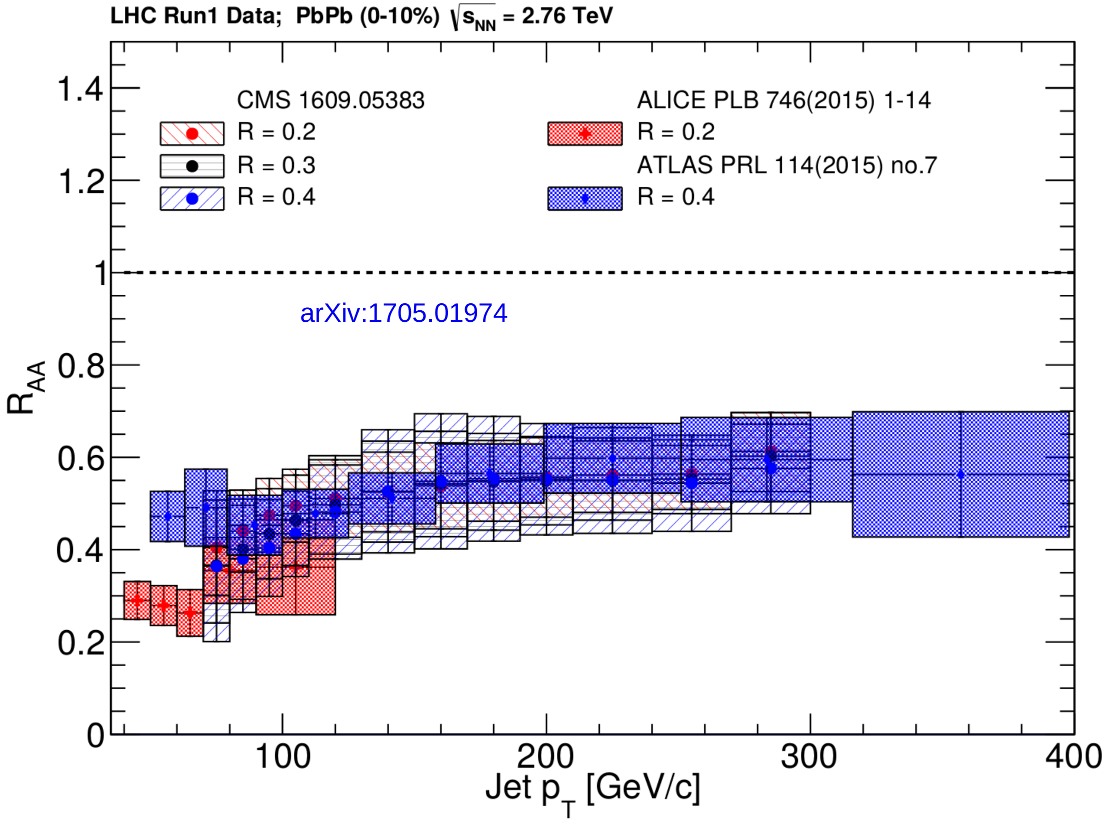
But they do matter down here!

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}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
100
200
300
400
Jet p_T [GeV/c]

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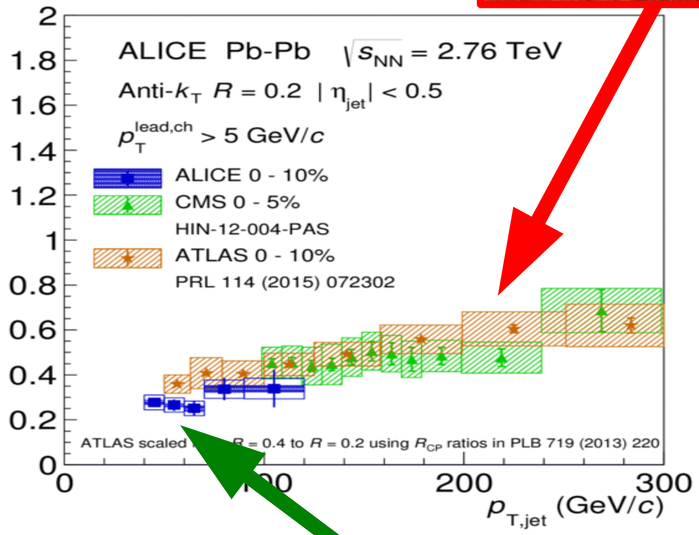
Phys. Lett. B 719 (2013) 220-241

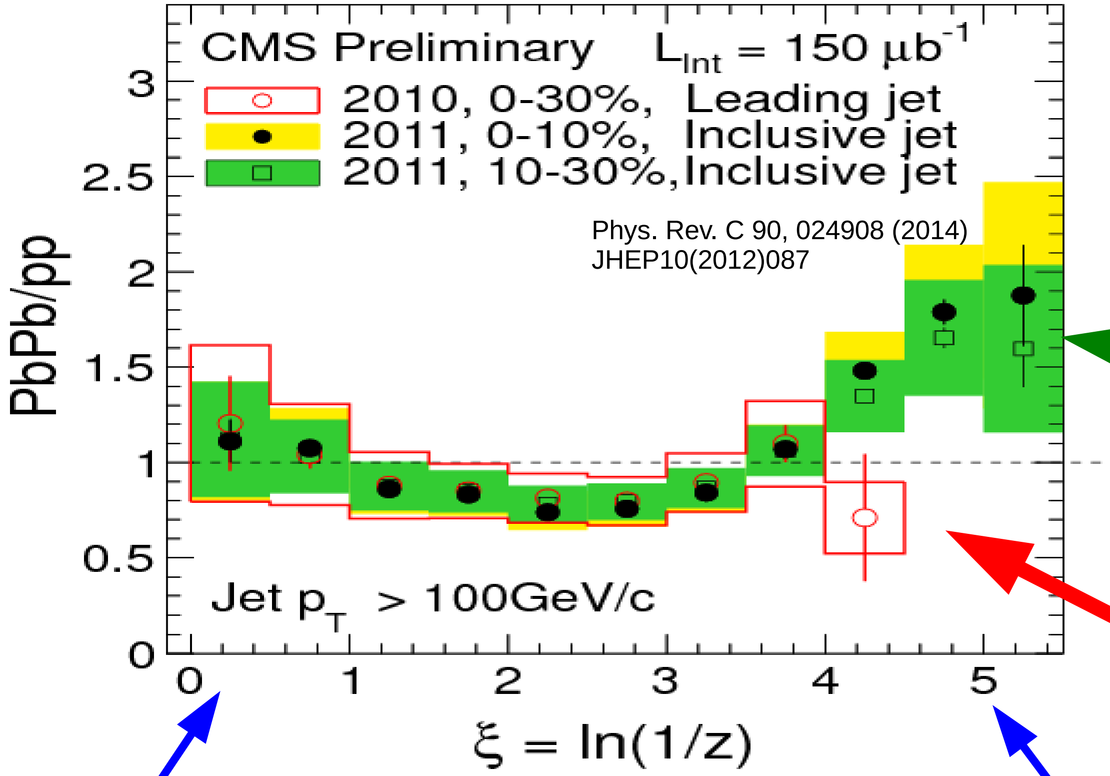


ALI-DER-92552

Constituent biases don't matter that much up here

But they do matter down here!

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

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

Analysis steps

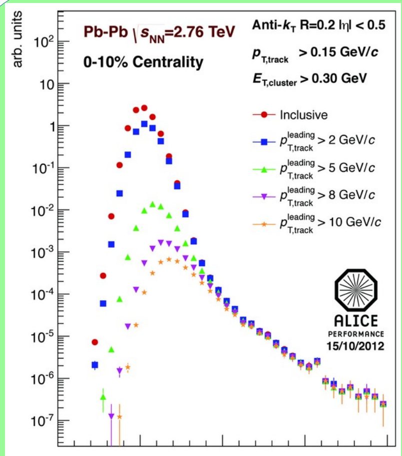
Tracks

Clusters

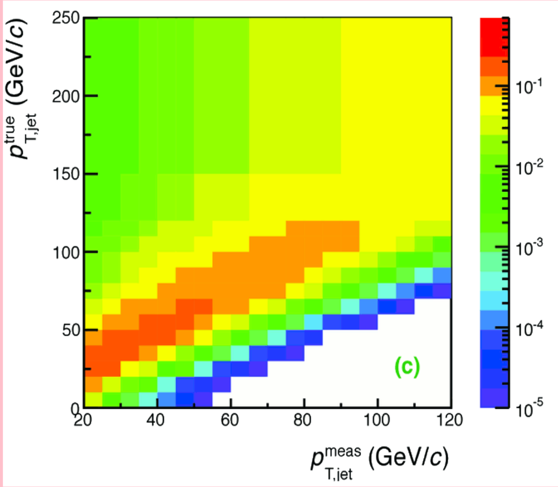
Jet finding algorithm

Jet candidates

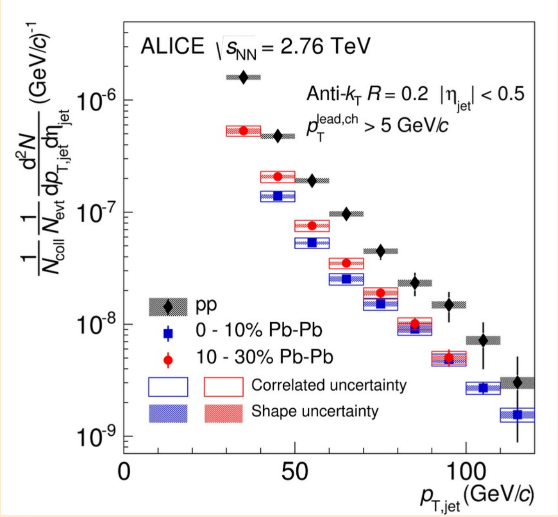
Background subtraction



Jet spectrum smeared by energy resolution, background fluctuations

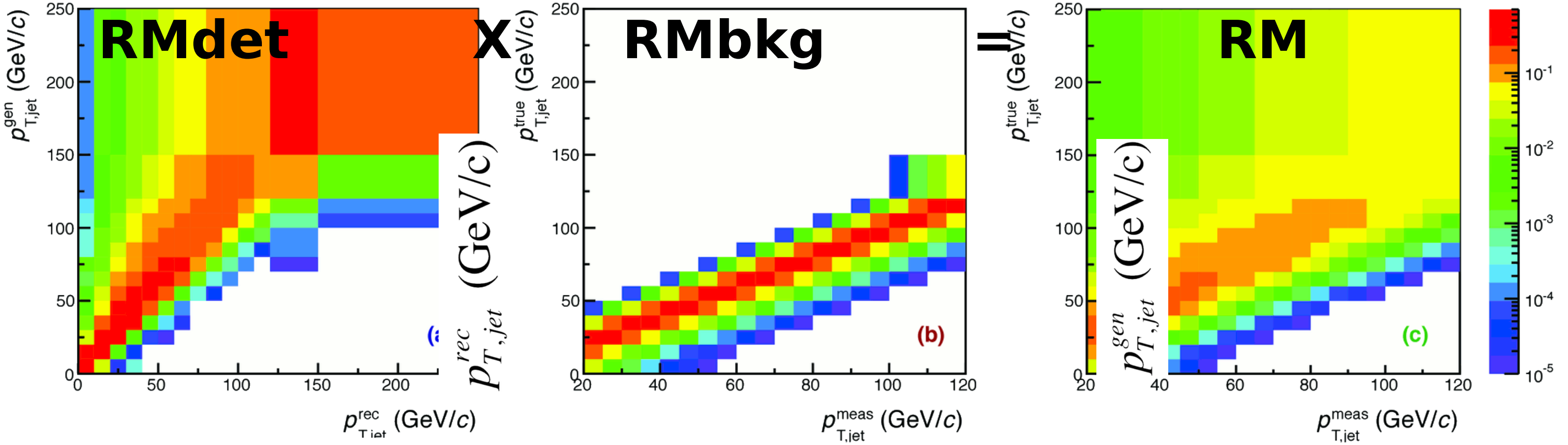


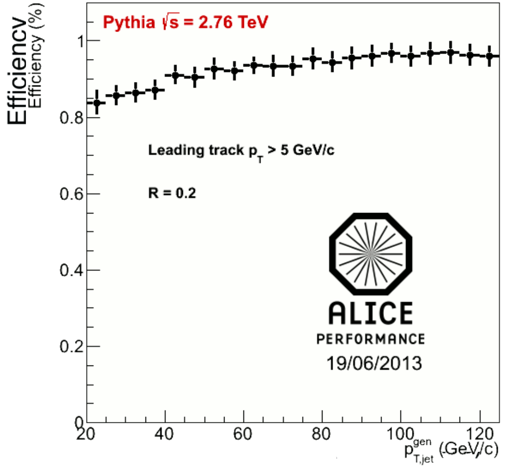
Unfolding – corrects for single track reco ε, E resolution, background fluctuations



Corrected spectra

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

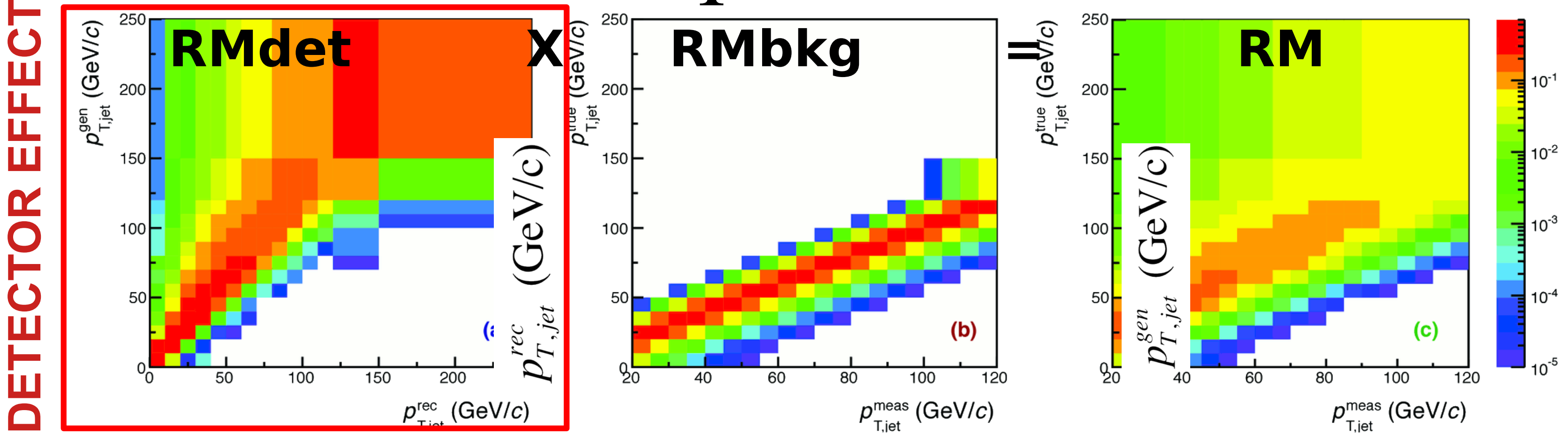
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

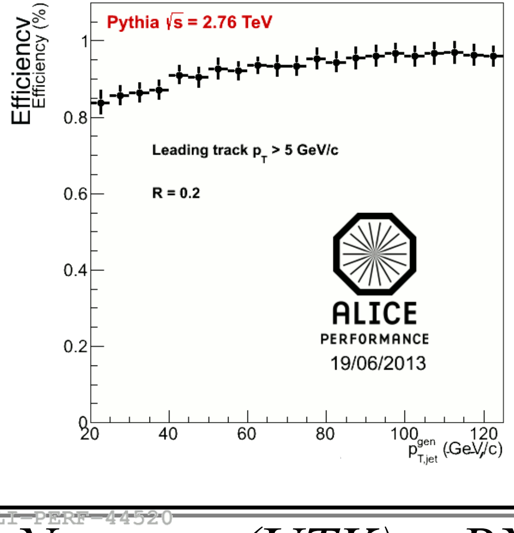
0-10% Centrality

ALICE
PERFORMANCE
15/10/2012

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

Jets in ALICE: Response Matrix Construction





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ALICE

PERFORMANCE

15/10/2012

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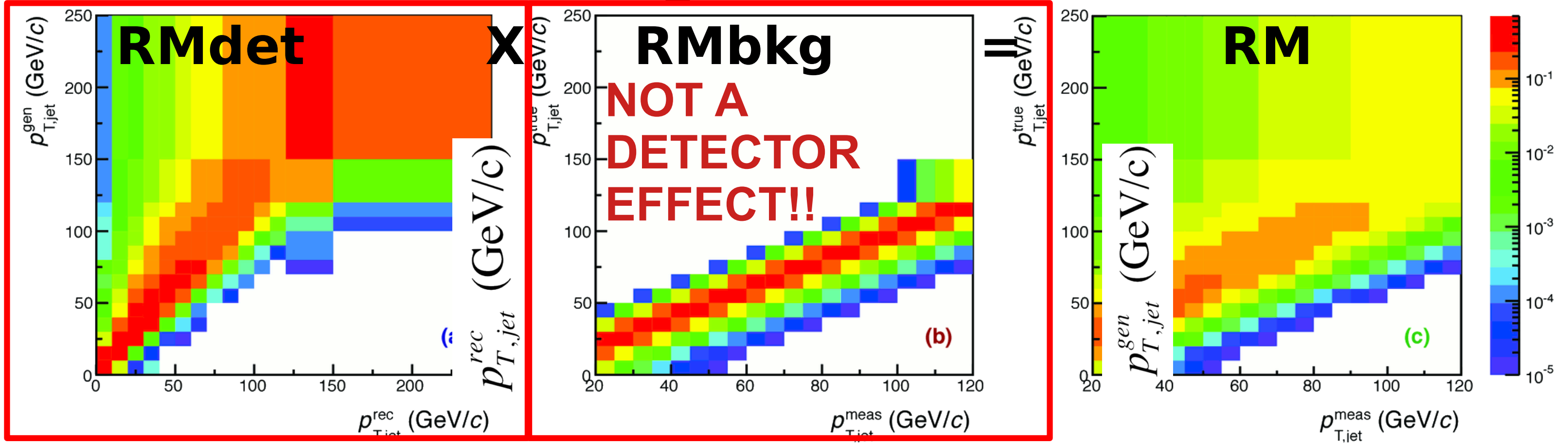
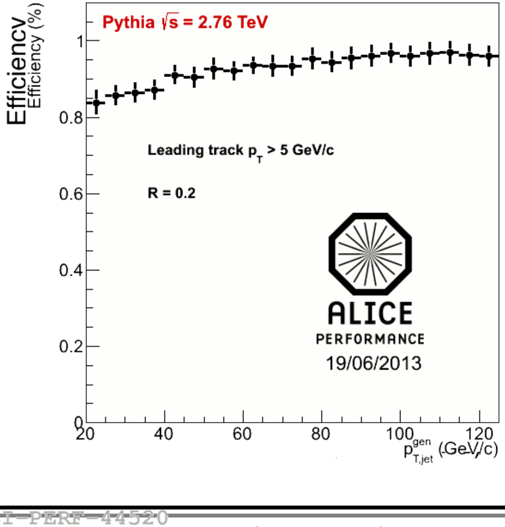
Jets in ALICE: Response Matrix Construction

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

Snowmass Accord: Forget the idea of a parton. 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

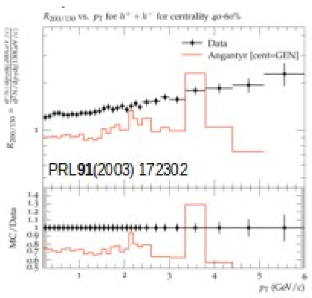
JEWEL
EPOS
PHSD
smash

HepMC

HEPData

Rivet

Comparison to data



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

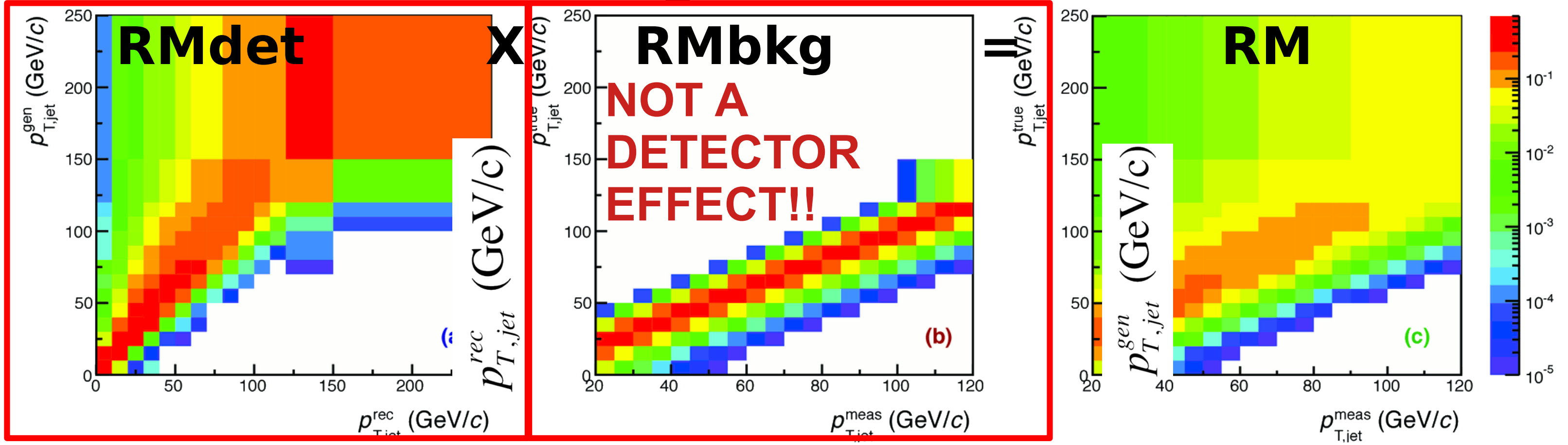
There are no materials yet.

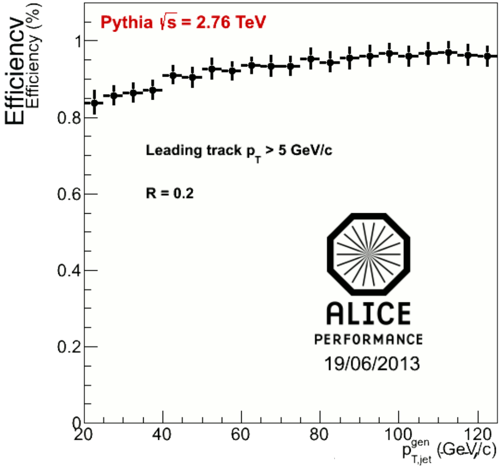
Registration
Registration for this event is currently open.

Register now

Jets in ALICE: Response Matrix Construction

DETECTOR EFFECT





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0-10% Centrality

ALICE

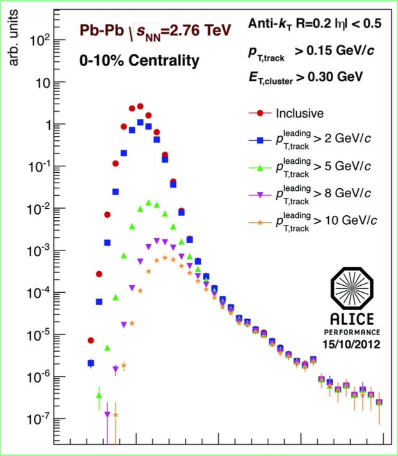
PERFORMANCE

15/10/2012

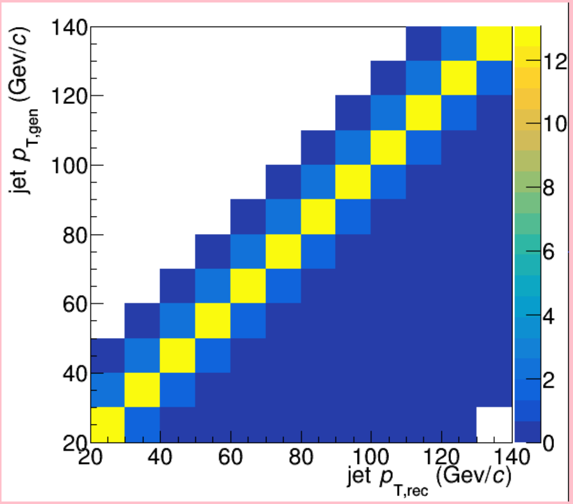
RM_{bkg} and RM_{det} are approximately factorizable

Analysis steps: Full Monte Carlo

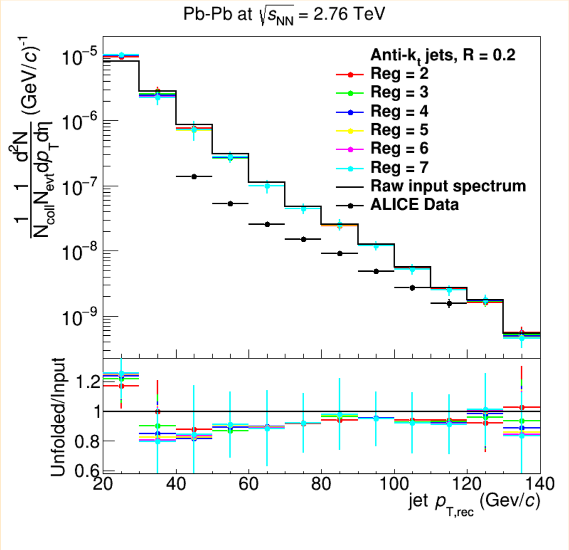
Particles → Jet finding algorithm → Jet candidates → Background subtraction



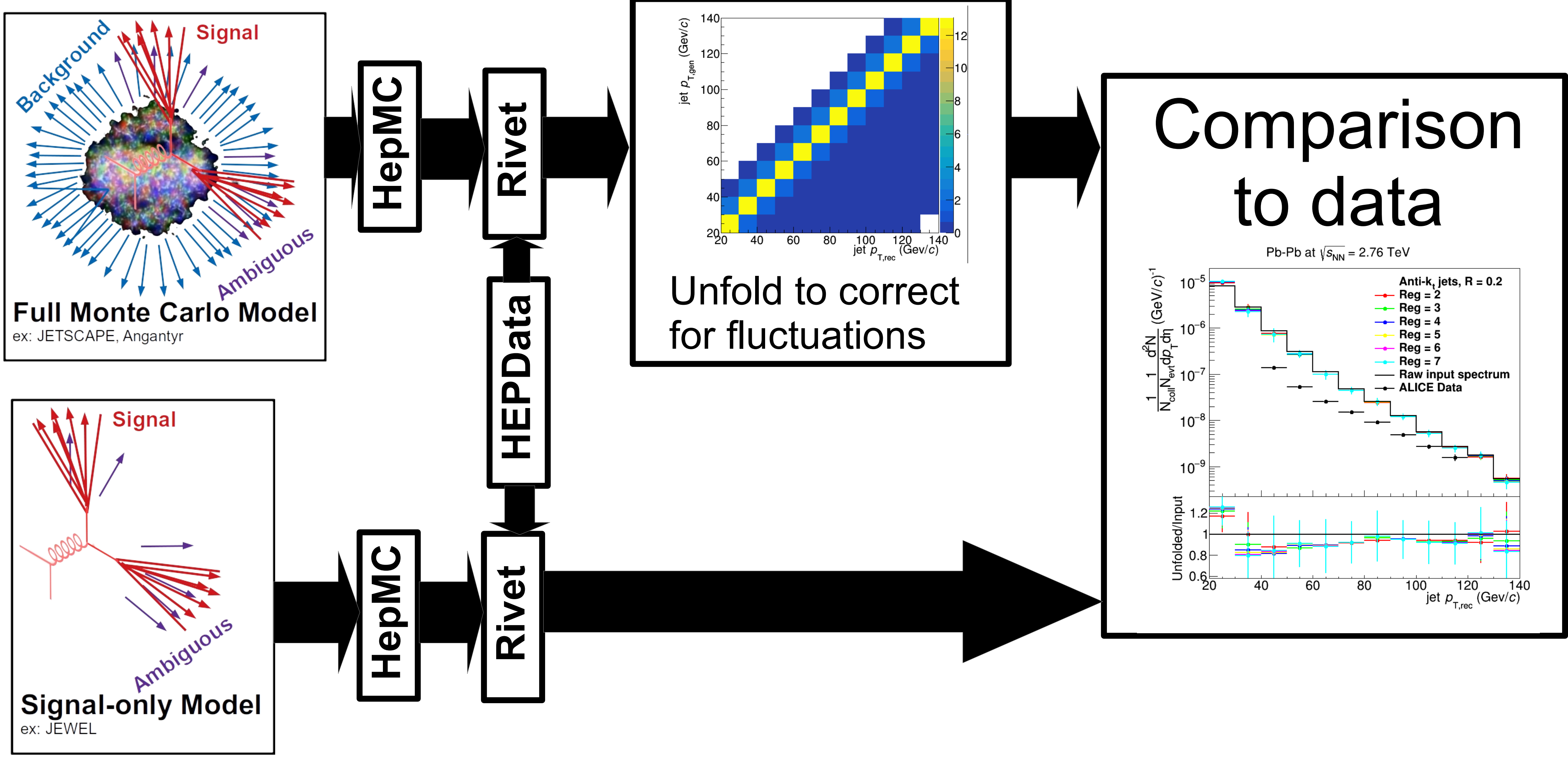
Jet spectrum smeared by energy resolution



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!

Summary

- Jets are defined by a jet finder and its parameters
- All jet measurements are somewhat sensitive to non-perturbative effects
- Background for jets in heavy ion collisions dominated by random combinations of particles
  - Other effects ~5%
  - Not described well by theory
- Measurements may have a biased selection of jets
- Conservative approach: Treat models like data → Rivet!