Hard Probes in Extreme Matter measured with the ALICE-Experiment

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for the ALICE Collaboration

1st EMMI Physics Days
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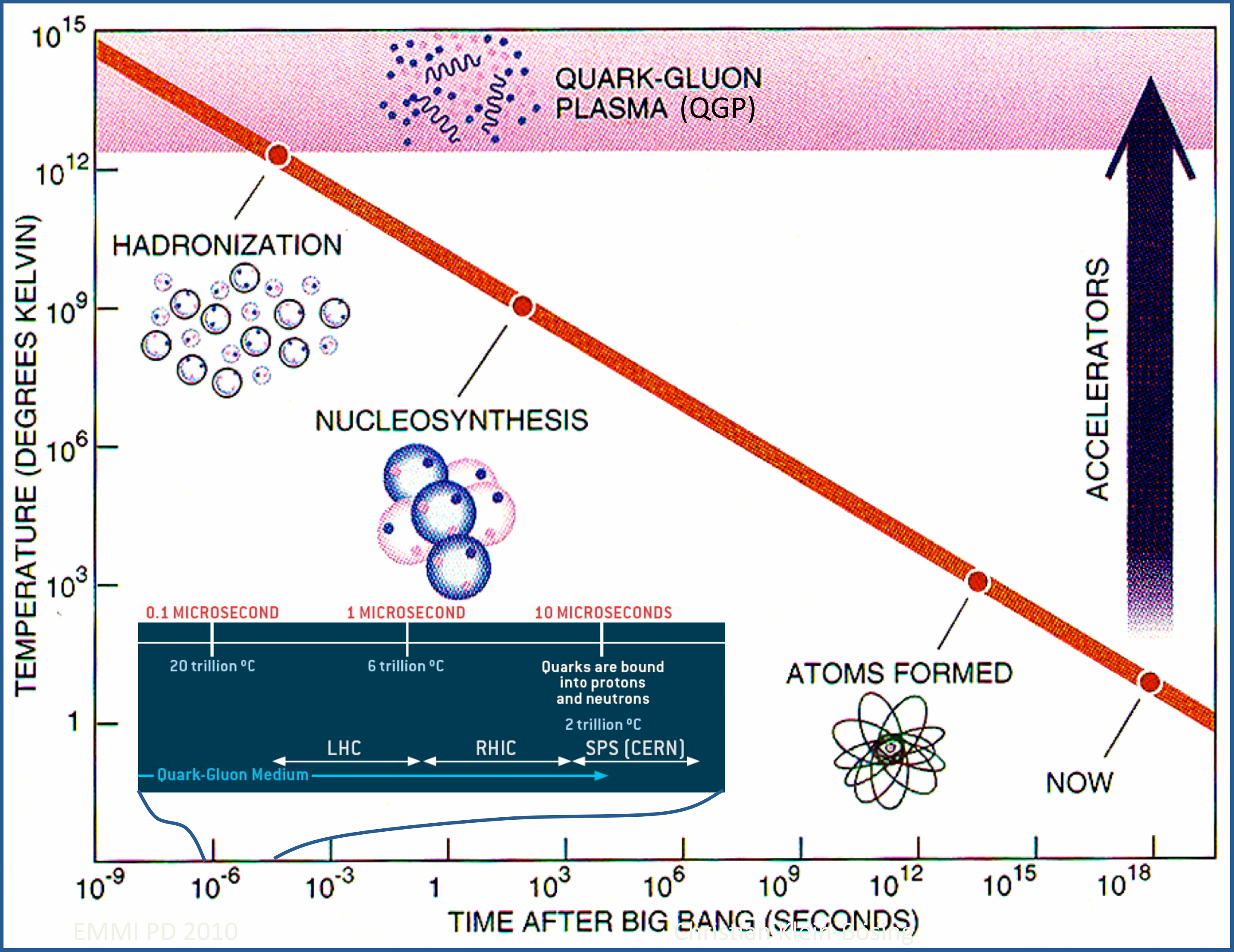
Outline

- Extreme Matter, Hard Probes and the ALICE Experiment
- Exploring a new energy regime in p+p
  - Minimum Bias events: Soft and semi-hard QCD
  - Jet properties
- Coming Up: Heavy-ion collisions

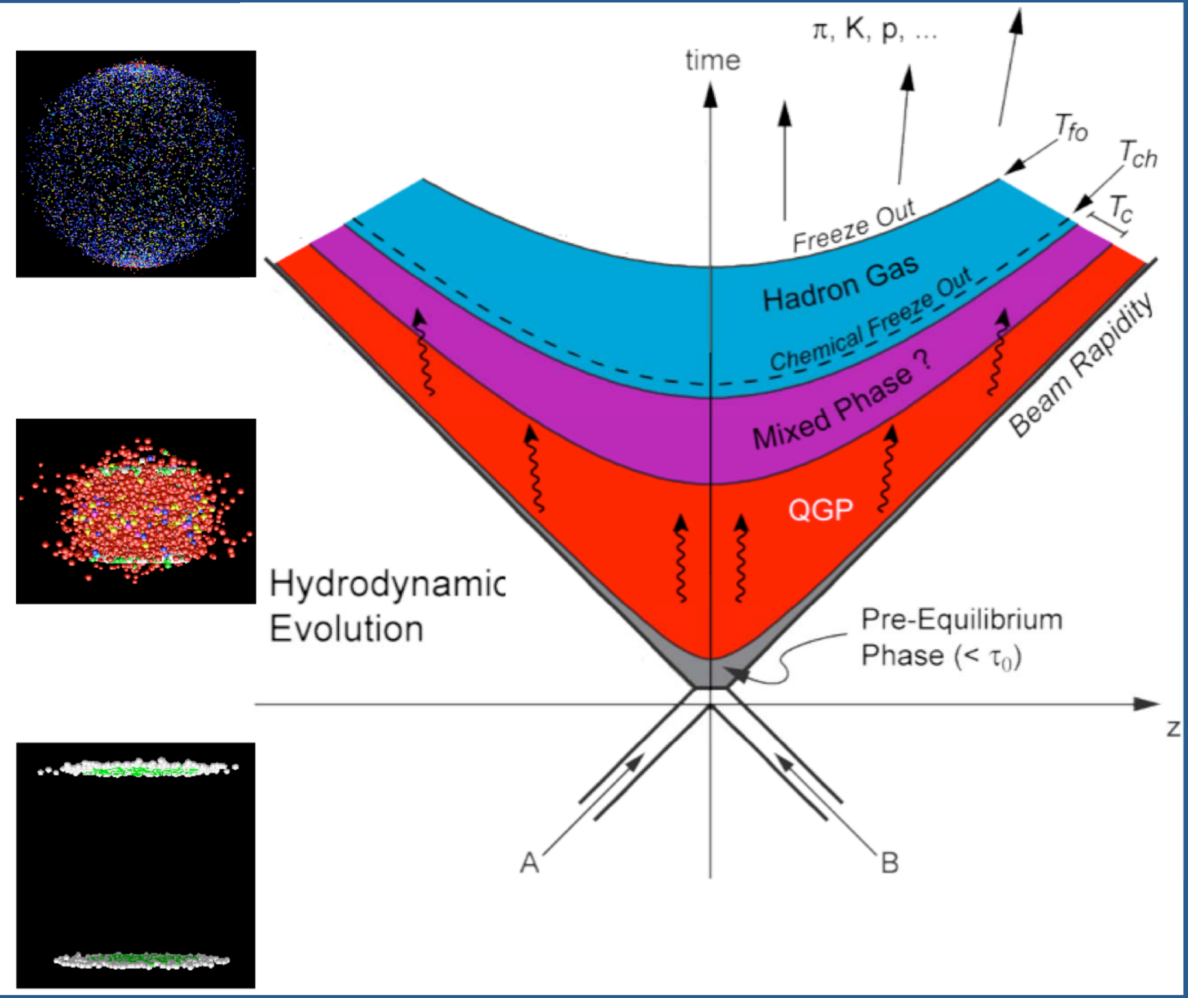
13.7 Billion Years ago: Extreme Matter, the Quark-Gluon Plasma



Quarks and gluons are not confined into hadrons but can move freely

Recreated in the laboratory by colliding heavy ions (e.g. Au, Pb)

Creation and Evolution of the QGP in Heavy-Ion Collisions



Expansion/
cool down

Time scale
O(fm/c) ~ O(10^{-23} s)

Thermodynamic parameters (T,μ_B) at freeze-out determine the **bulk** of particle production.

Want to probe the evolution of the QGP: need early production, (« 1 fm/c) and strongly interacting particles.

Recap: Hard Probes

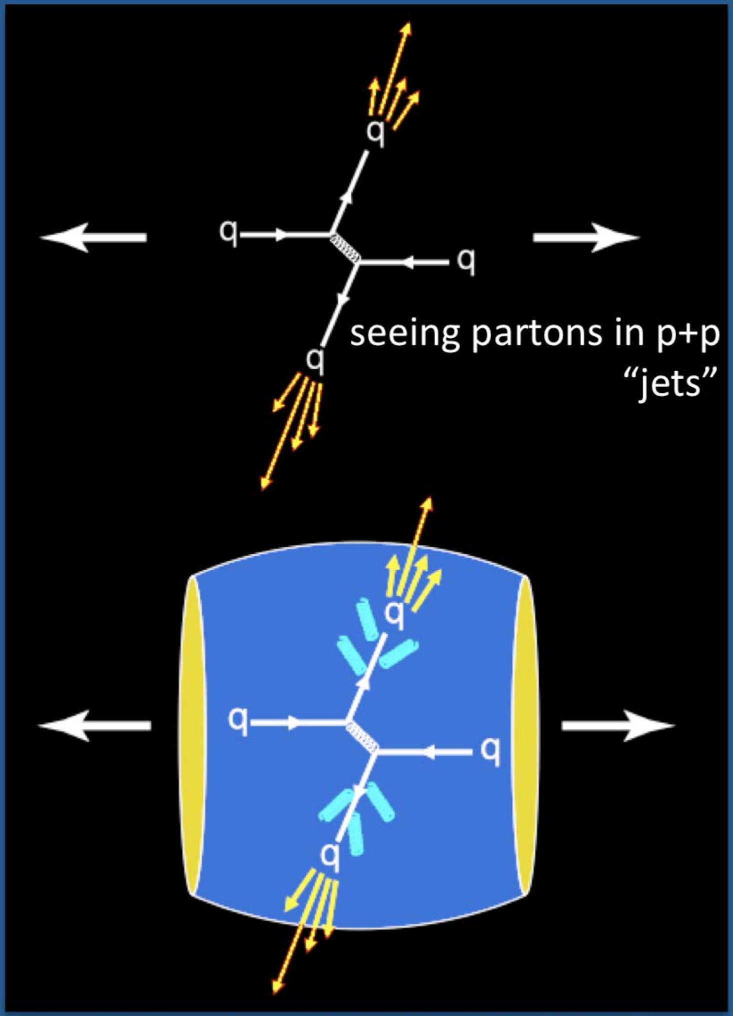
- Hard probes
  - $t \sim 1/Q \ll 1$ fm/c (rare)
  - Hard scale set by momentum or mass (**high p_T** or heavy flavor)
- Parton scattering with large Q^2
  - Partons fragment into "jets" of observable hadrons
    - Strong back-to-back correlation
  - Main source of particle production at **high** p_T

$$\frac{d^2\sigma_h}{dp_T dy} = \int \text{PDF} \times \text{pQCD} \times \text{FF}(q, g \rightarrow h)$$

  - In A+A: High p_T partons interact with QCD medium prior to fragmentation **("*jet tomography*")**

$$\Delta E \propto \alpha_s C_R \langle \hat{q} \rangle L^2 f(E, m_q)^*$$

Scattered parton properties (including medium effects) reflected in high p_T particles/jets.

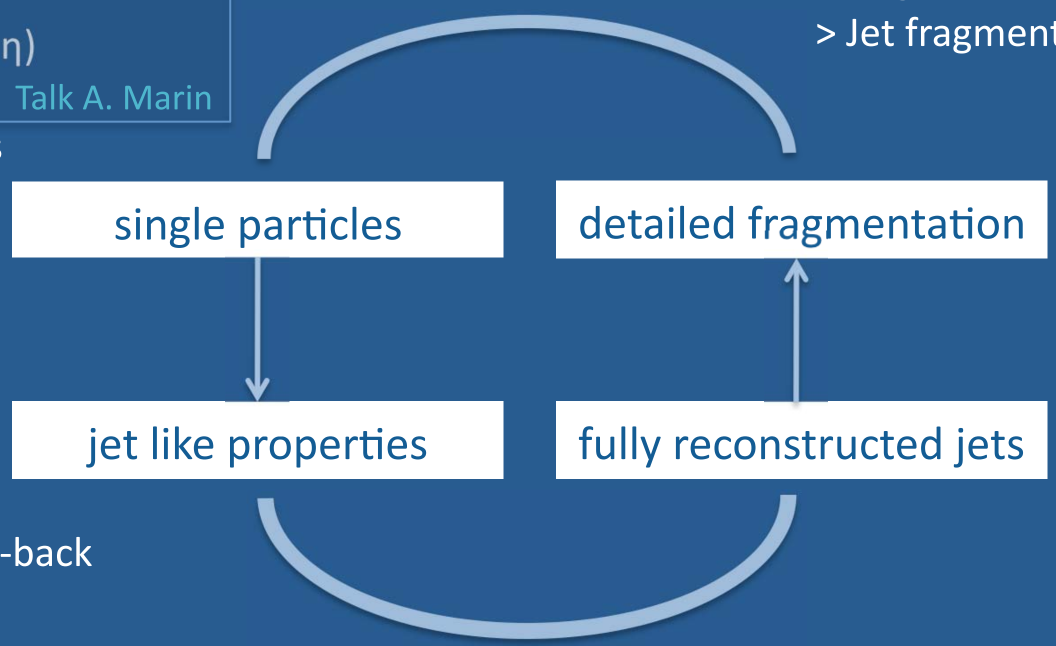


*E.g. Baier et. al NPB 484: 265 (1997)

Accessing Hard Probes

Bottom-Up: Single particles
Spectra at high p_T
> Leading particles
> Identified hadrons (π^0, η)
> Prompt photons   Talk A. Marin
Two-particle correlations

Top-Down: Fully reconstructed jets
> Spectrum
> Angular distribution
> Jet fragmentation



Jet-like properties:
> Spectral shape, back-to-back correlation

Experimentally clearly defined.
Bias: Hard fragmentation.

Directly related to theoretically well defined parton properties.
Depend on jet definition.

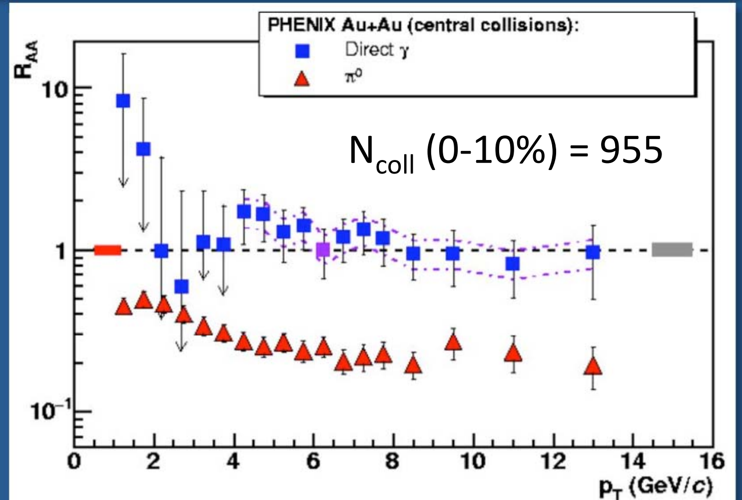
Single Particles @ RHIC
The Nuclear Modification Factor

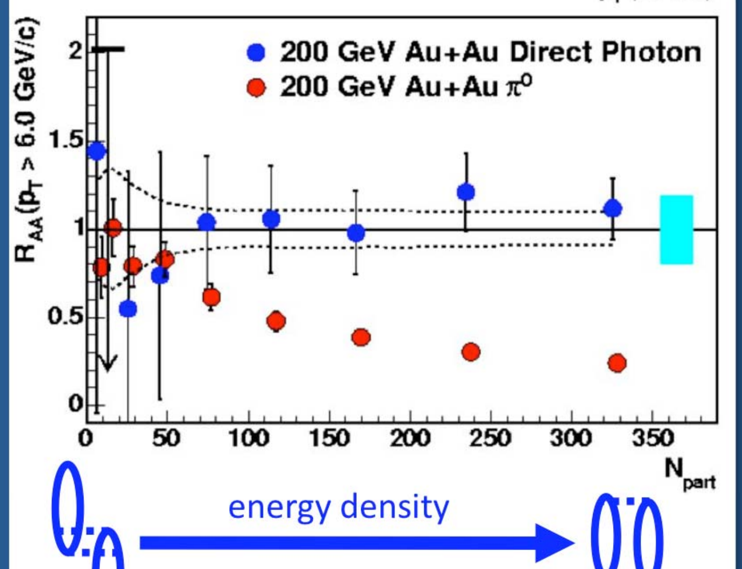
- Compare spectra in p+p and A+A ("transmission coefficient")
  - T_{AA} accounts for increased parton flux in A+A

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{T_{AA}\, d^2\sigma_{pp}\, dydp_T} \qquad T_{AA} = N_{coll}/\sigma_{NN}$$

- Observation:
  - Strong suppression for hadrons/jet leading particles
  - No suppression of photons
    - Also produced in hard scattering but electromagnetic probe
    - Proof that hard scattering occurs at the expected rate

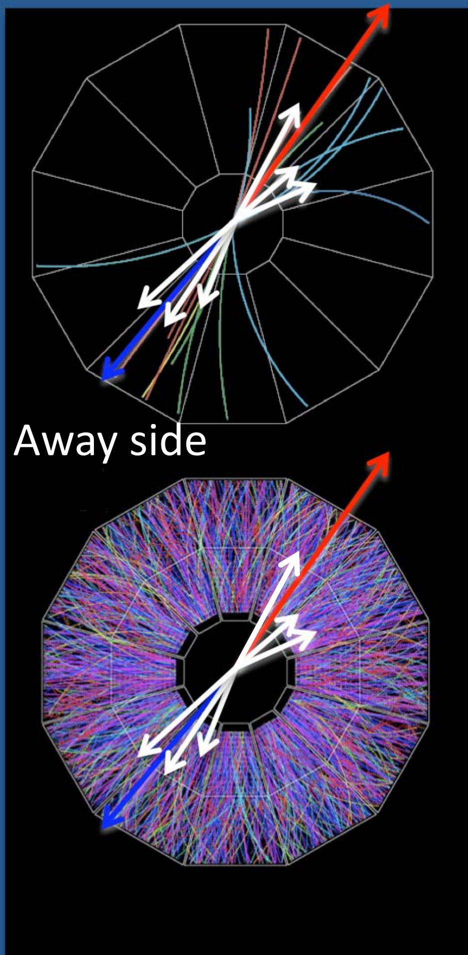
Strong final state effect in central Au+Au





PRL **94** 232301 (2005)

Single Particle @ RHIC Correlations

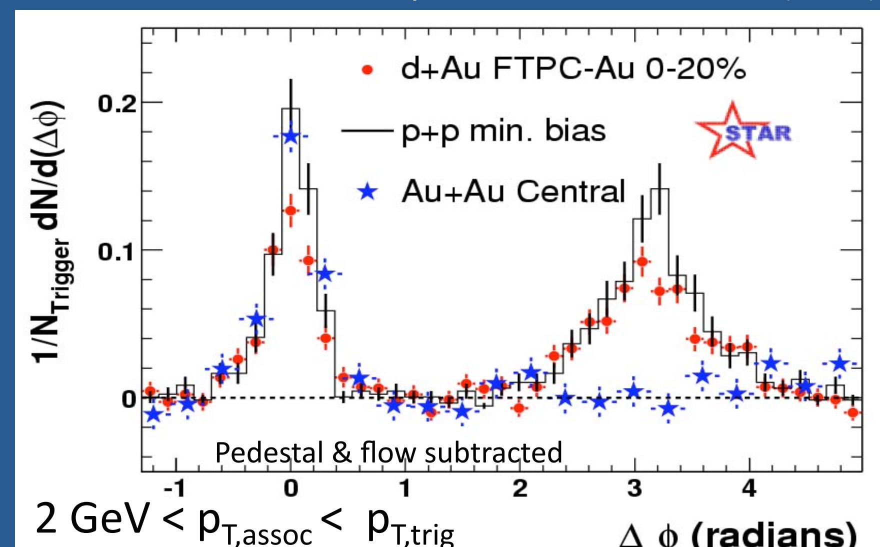


Near side

4 GeV < $p_{T,trig}$ < 6 GeV

- Apparent jet-like structure in p+p and d+Au
- Suppression of the away side jet correlation in central Au+Au

Phys. Rev. Lett. 91, 072304 (2003)



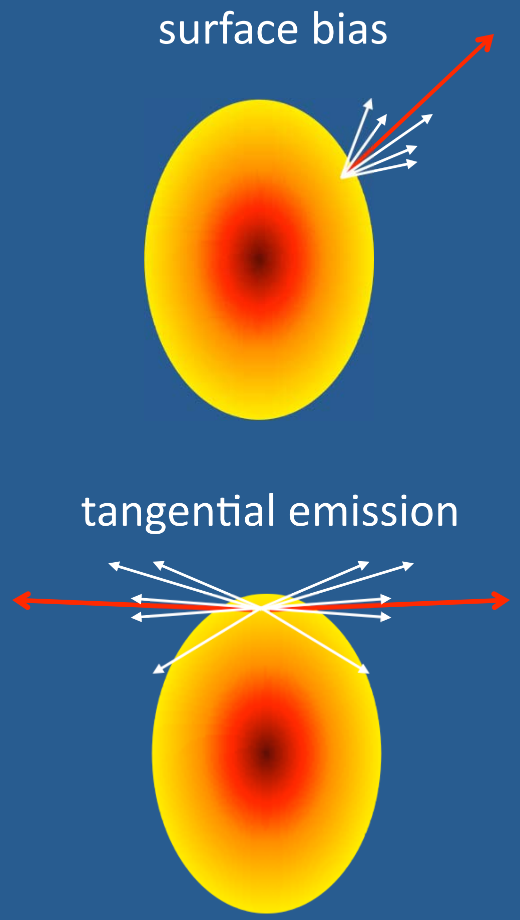
Strong final state effect in central Au+Au

Limitations of Single Particle Measurements

- Access to parton information convoluted with fragmentation process

$$E\frac{d^3\sigma^{hard}_{NN\to h}}{dp^3} = \sum_{a,b,c} f_a(x,Q^2)\otimes f_b(x,Q^2)\otimes \frac{d\sigma^{hard}_{ab\to c}}{d^3p}\otimes D_{c/h}(z,Q^2)$$

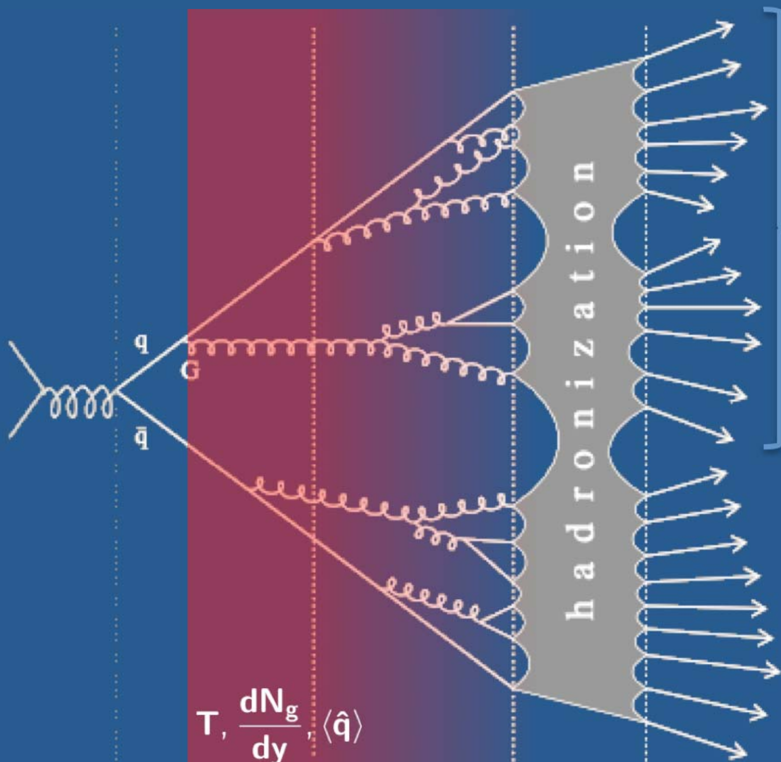
  – Trigger bias from leading particle on hard fragmentation ($<p_{T,leading}/p_{T.jet}> \approx 0.7$ @ RHIC)
- In A+A
  – Selecting high p_T particle favours unquenched jets
    - Closer to surface
  – Correlation studies favour tangential emission
  – (Simplified) black and white picture
    - See only leading particle from a thin skin
    - Little sensitivity to path-length, hot core

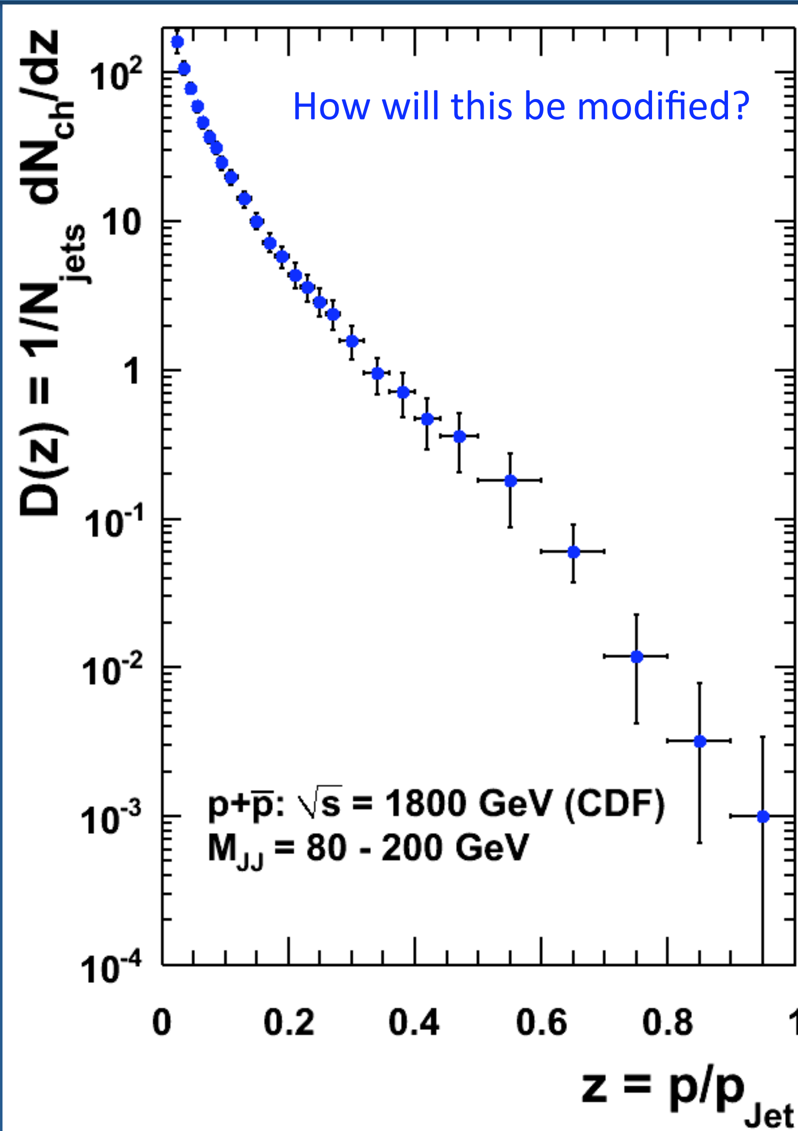


Solution: Full jet reconstruction weakens bias and allows to study jet *modification* in A+A compared to p+p.

Modification of Jet Fragmentation

A+A





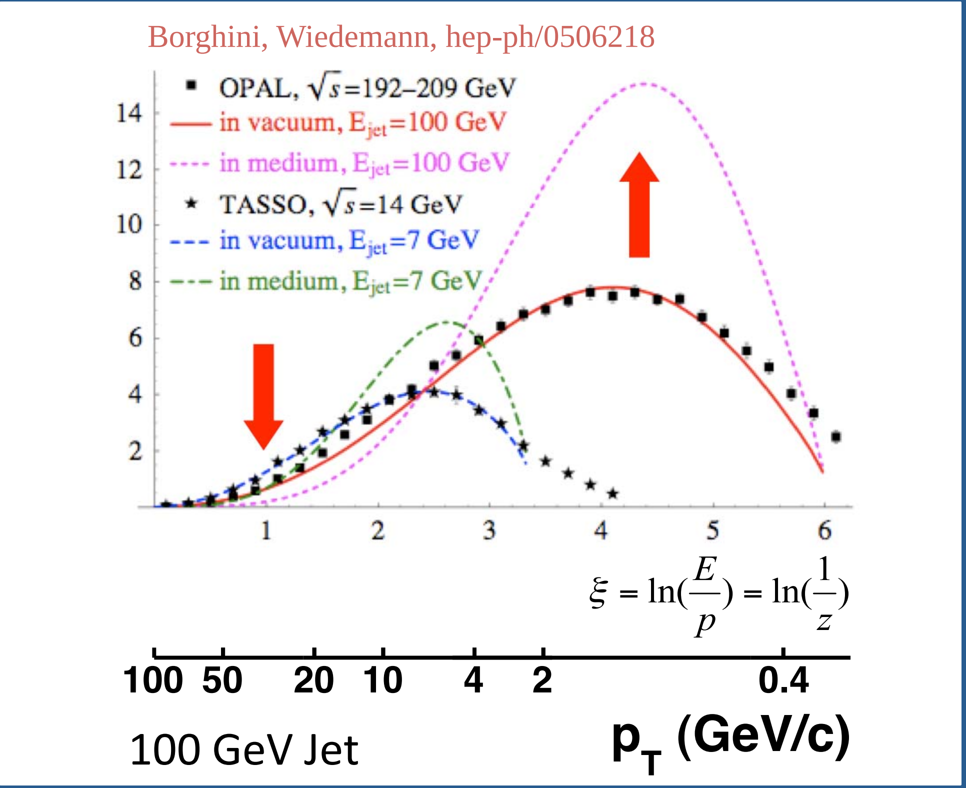
+ underlying event (hard: ~ N_{coll} – 1 p+p) and thermal bulk (can couple to the jet)

Modification of Jet Fragmentation

- Convenient to emphasize low p_T

$$\xi = \ln\frac{E_{jet}}{p_{hadron}} = \ln\frac{1}{z}$$

- Decrease of leading particle p_T (energy loss) as seen in hadron R_{AA}
- Increase of p_T relative to jet axis (j_T-broadening)
- Increase of the number of low p_T particles (radiated energy)
- A large dynamic range in p_T is needed to capture the full modification

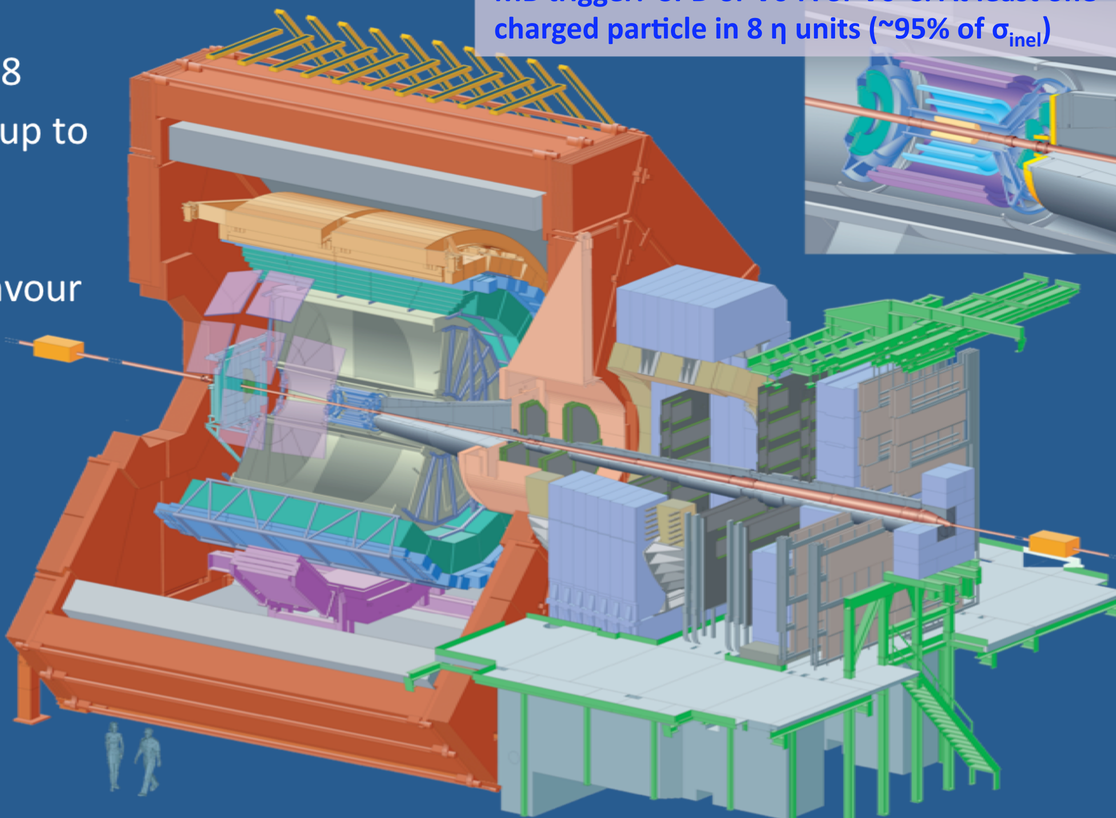


Search for redistribution of energy in the jet. Need to measure particle production in jets at low p_T.

The ALICE Central Detectors

- ITS TPC TRD (40%) TOF HMPID
  - Charged particle tracking, $\Delta\eta$ = 1.8
  - Excellent momentum resolution, up to 100 GeV/c $\Delta p/p$ < 6%
  - Tracking down to 100 MeV/*c*
  - Excellent particle ID and heavy flavour tagging
  - TRD: high p_T and electron trigger
- EMCal (40%)
  - Energy of neutral particles
  - $\Delta\phi = 107^\circ$, $\Delta\eta = 1.4$
  - Energy resolution ~10%/√E_γ
  - Jet and γ trigger
- PHOS (20%)
  - $220^\circ < \phi < 320^\circ$, $\Delta\eta = 0.24$
  - Energy resolution ~ 3%/√E_γ
  - γ trigger

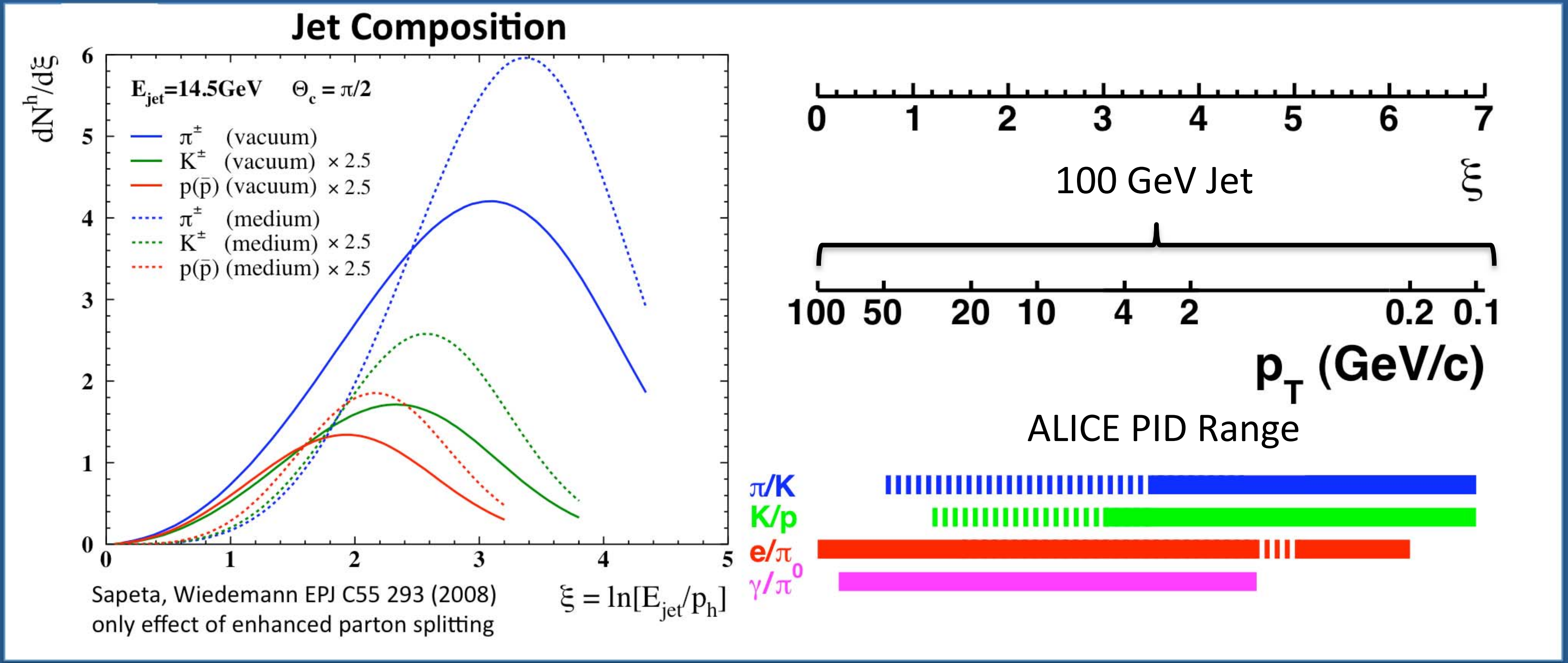
MB trigger: SPD or V0-A or V0-C: At least one charged particle in 8 η units (~95% of σ_{inel})



Understand soft QCD in a new energy regime.
First high p_T physics: Jet like properties of single particles and start of jet reconstruction.

Decomposing the Fragmentation Function

More detailed look at the fragmentation function:
composition (affected e.g. by recombination, and colour flow of the parton shower)



ALICE is the ideal instrument for these studies.

No signal without “Background”

± Underlying Event

soft QCD

- p+p: diffraction, multiple parton interaction. string breaking
- A+A: thermal medium, hydrodynamic evolution, statistical hadronization.

larger background and direct influence **soft ⊗ hard**

single particles

detailed fragmentation

jet like properties

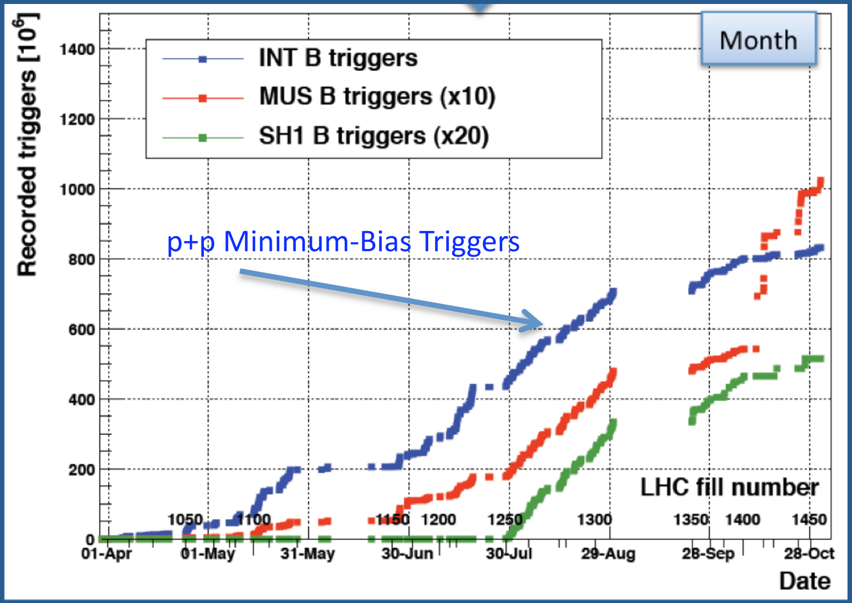
fully reconstructed jets

To study the effect of the medium on the evolution of jets we have to subtract the underlying event and understand its differences in p+p and A+A.

p+p Collisions with ALICE: A new Energy Regime

- Explore QCD in the non-perturbative regime
  - Soft and semi-hard QCD
  - Particle production, total multiplicity
- Connect high p_T observables with low p_T measurements
  - Hadronization properties of jets
- Provide reference for Pb+Pb
  - Comparison to QCD vacuum
  - Quantify N+N background in Pb+Pb (Corona)

ALICE Collected Data



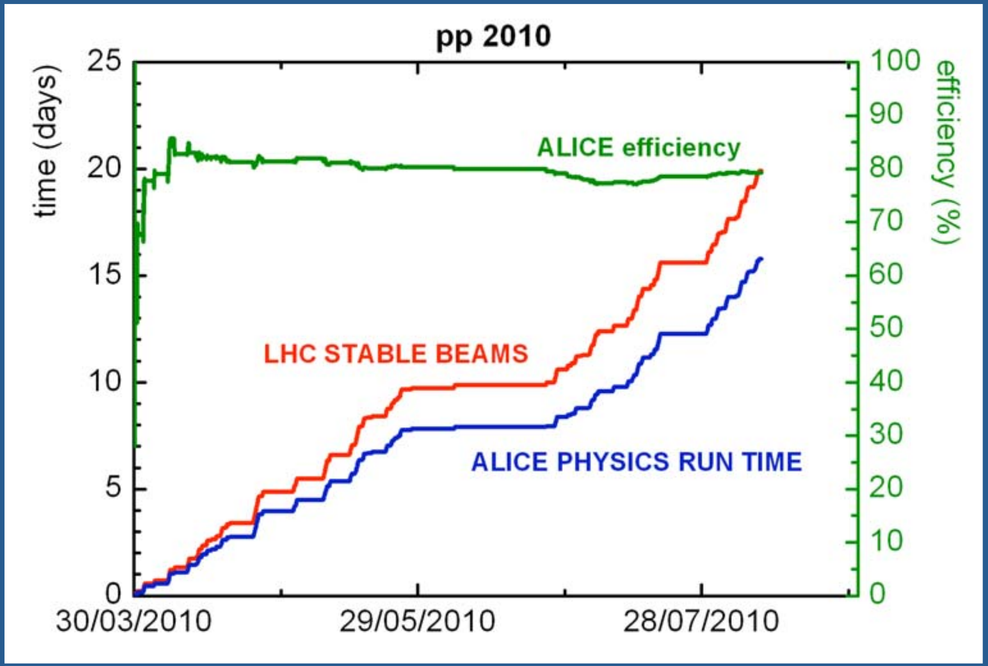
Mainly 7 TeV

Emphasis on MB data for (x-section measurements)

> + high multiplicity triggers in low-pile up mode

> + last week(s) high lumi data with muon triggers

ALICE operates at constantly high efficiency.



> 800 M minimum bias pp collisions @ 7 TeV

LHC p+p Collisions

900 GeV	**(Start-up)**
2.36 TeV	**(Testing)**
7 TeV	**(Until yesterday)**

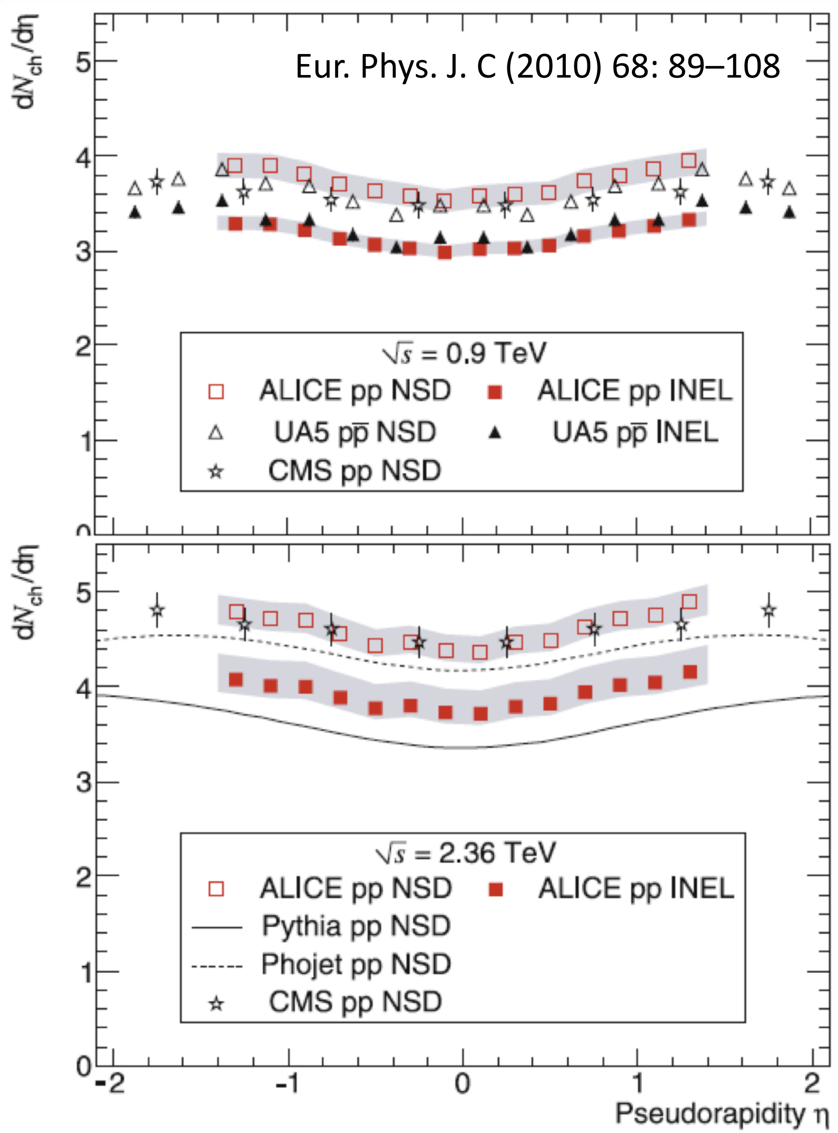
LHC Pb+Pb Collisions

2.75 TeV	**(Sunday!)**

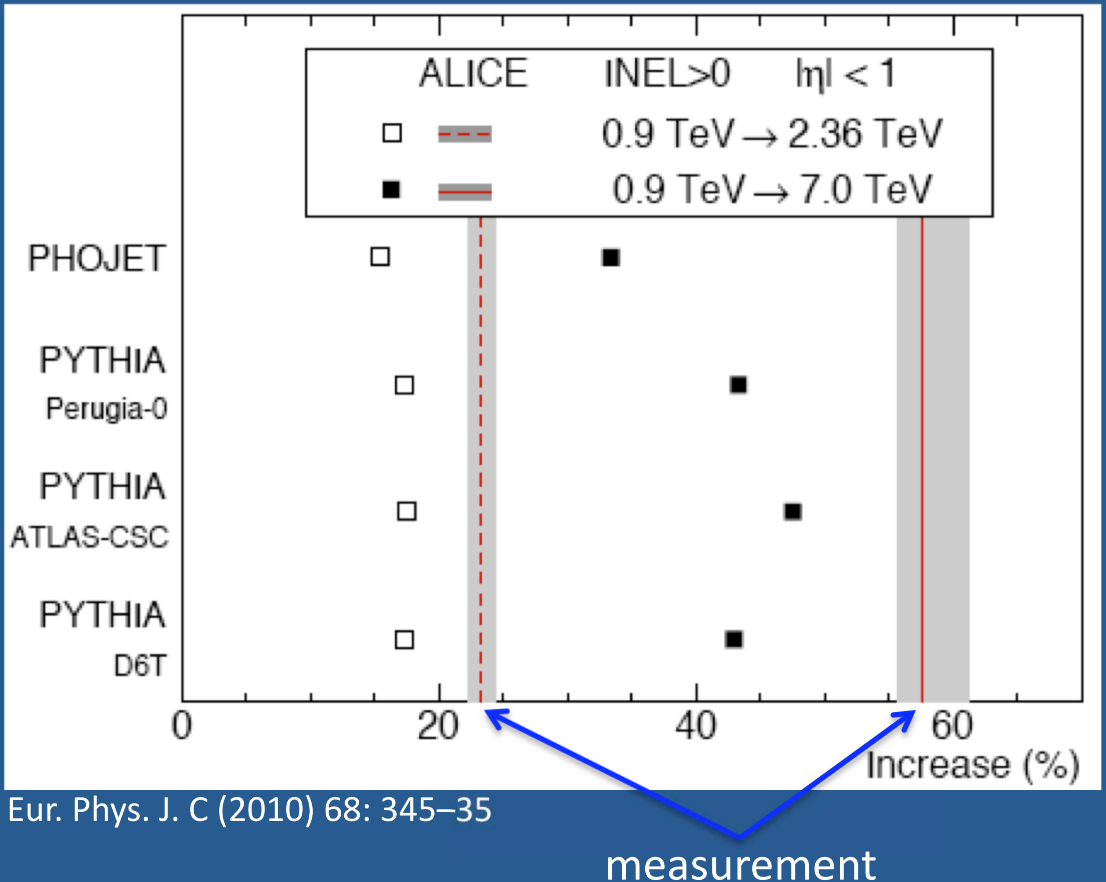
Characterizing Particle Production: Counting Charged Particles (dN/dη)

- Total Particle production dominated by soft processes
  - Constrains phenomenological models and event generators
- Measurement
  - Track segments in the inner tracking detectors (SPD)
  - Trigger:
    - INEL: V0-A || SPD || V0-C
    - NSD: V0-A & V0-C

Consistency between LHC experiments.
Large discrepancy to PYTHIA (Tune D6T) .



Increase with Beam Energy



Eur. Phys. J. C (2010) 68: 345–35

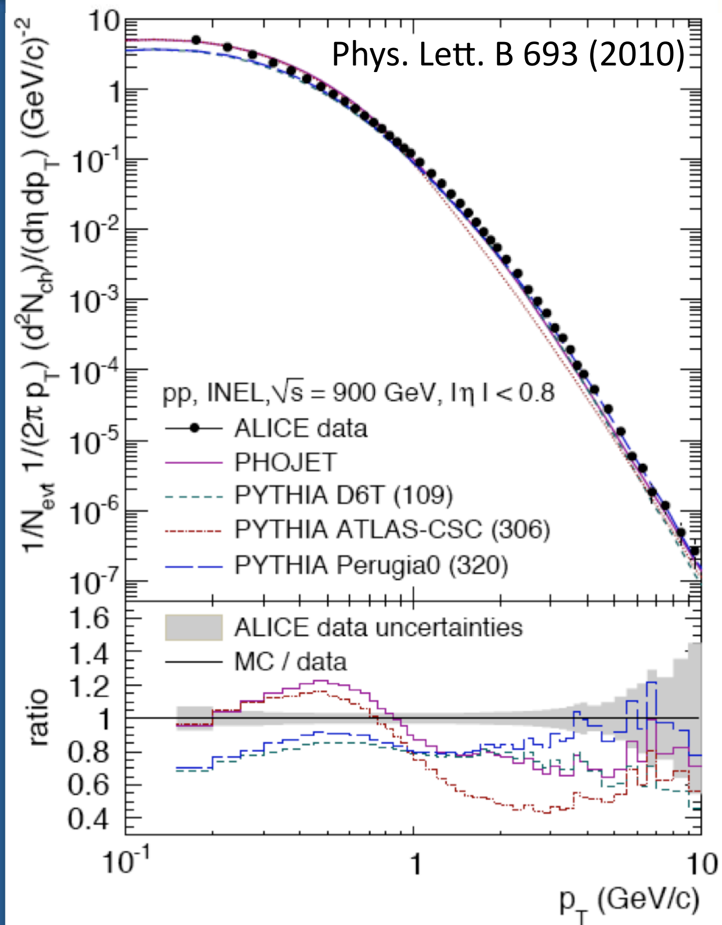
- Multiplicity for events with at least on charged particle in |η| < 1
- Increase from 0.9 → 2.36 (→ 7 TeV) not reproduced by standard generators/ tunes
- Effect of more multiple parton interactions?

Need to improve our understanding of particle production in p+p: baseline and corona for Pb+Pb.

Momentum Distribution: Charged Hadrons in p+p @ 900 GeV ($d^2N/dp_Td\eta$)

- First ALICE measurement of charged particle spectra
- 213k events after selection
  - MB trigger & bunch crossing
  - Reconstructed vertex position
  - Veto on beam gas and cosmics (timing cuts, vertex constraints, visual scanning)
- Track cuts
  - Combined ITS and TPC tracking
  - Fit quality cuts (χ2, number of clusters…)
  - Secondary rejection (DCA to vertex)
- Reference measurement for R_{AA}
  - Lower √s for interpolation

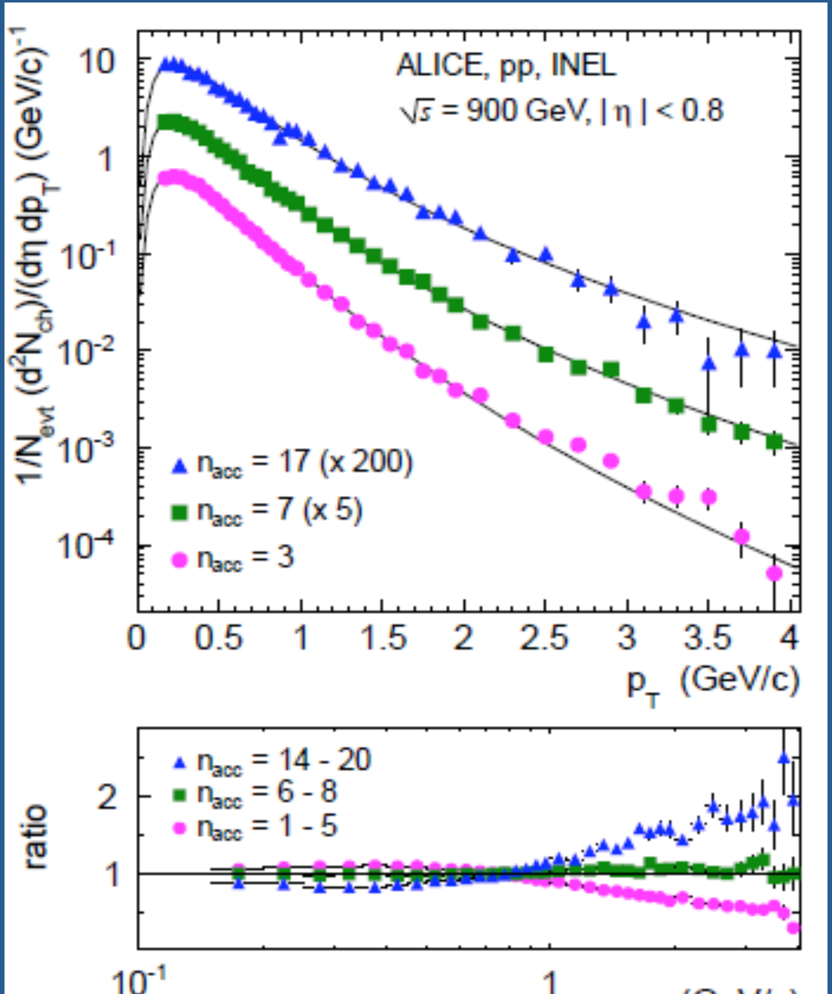
Power law above p_T = 2 GeV/c, suggestive of pQCD point-like scattering. 97 % of all particles lie below.



Not well described by MCs.

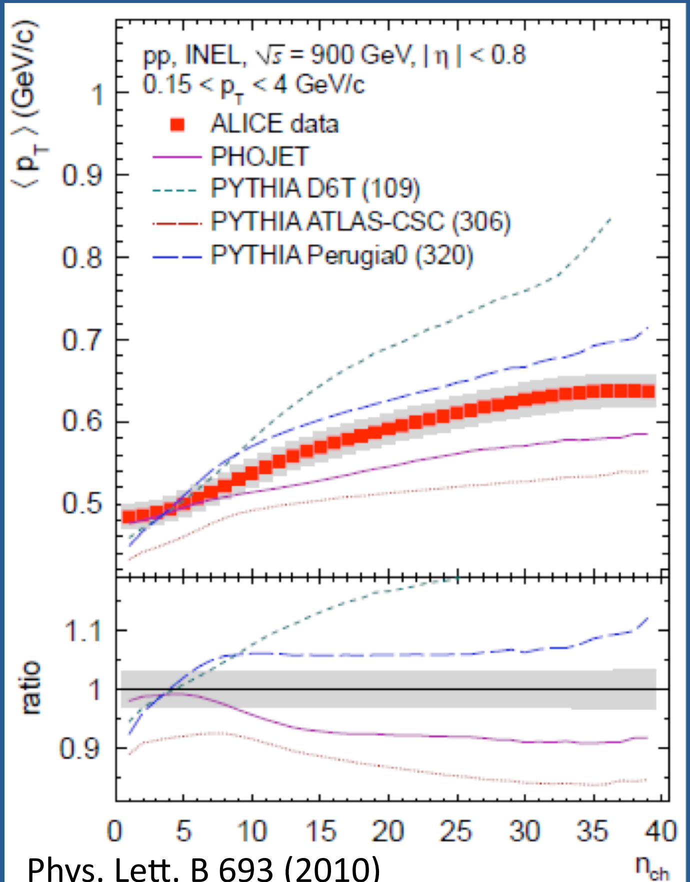
Relation between p_T and Multiplicity

p_T for different multiplicities



Phys. Lett. B 693 (2010)

Average p_T vs. multiplicities

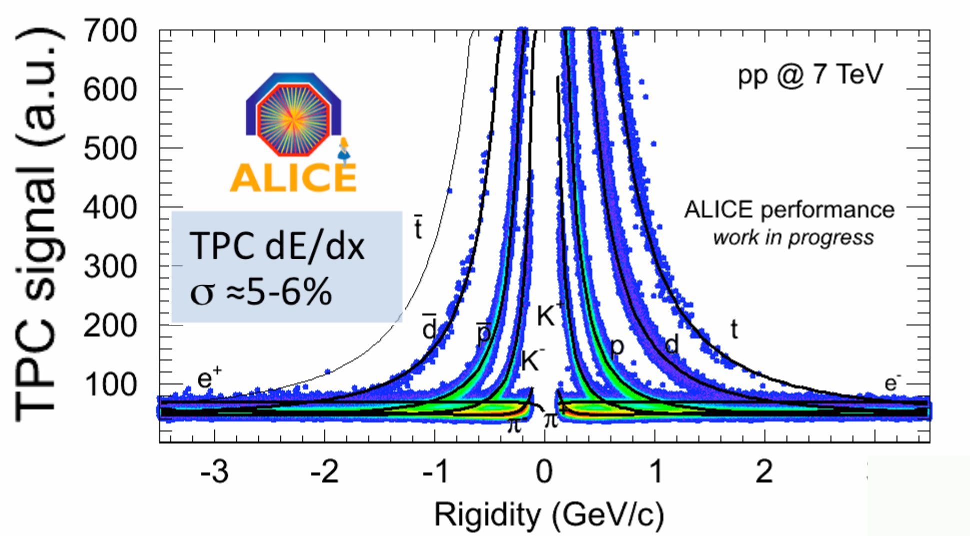


Phys. Lett. B 693 (2010)

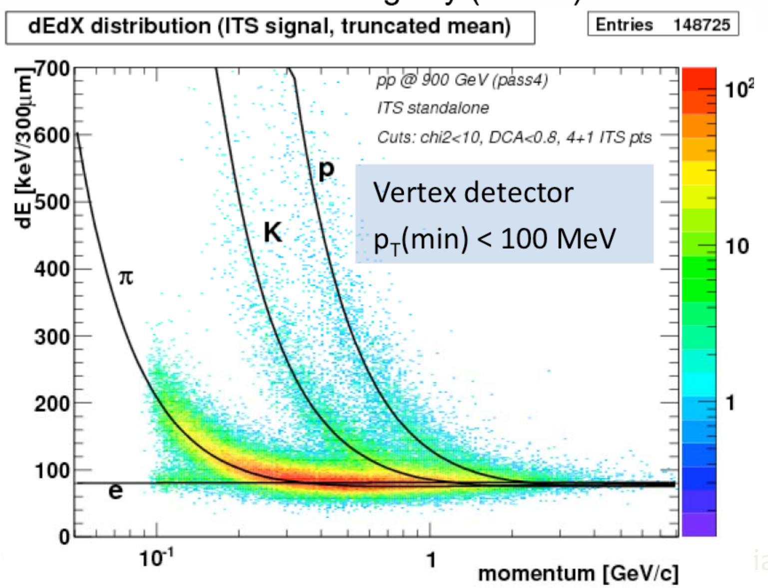
Change concentrated at p_T > 1 GeV (pQCD).

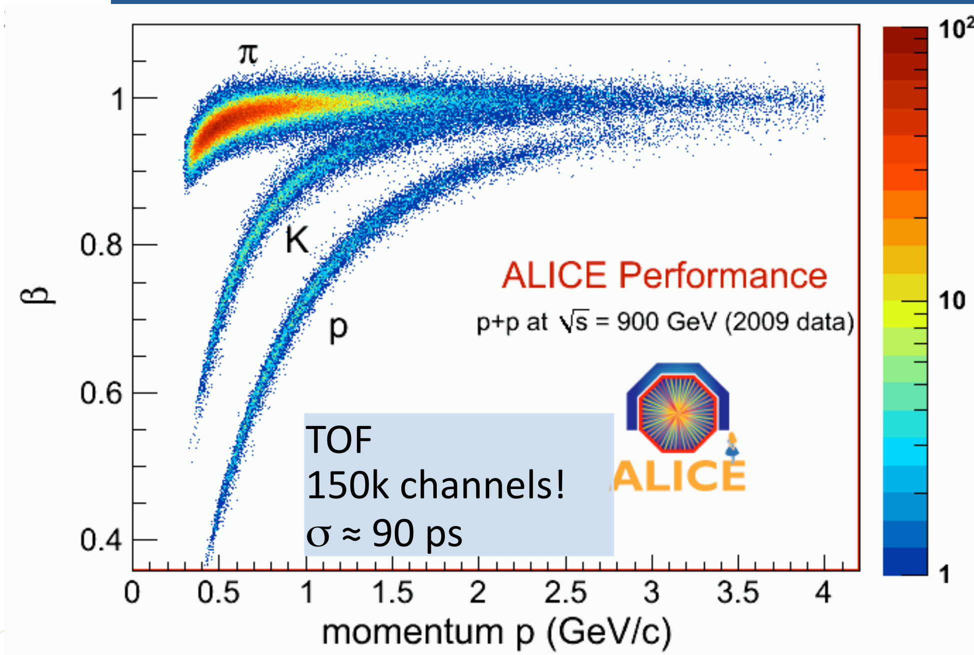
MCs do not reproduce the data.

Adding PID
$d^2N/dp_Td\eta \rightarrow d^2N/dp_Tdy$

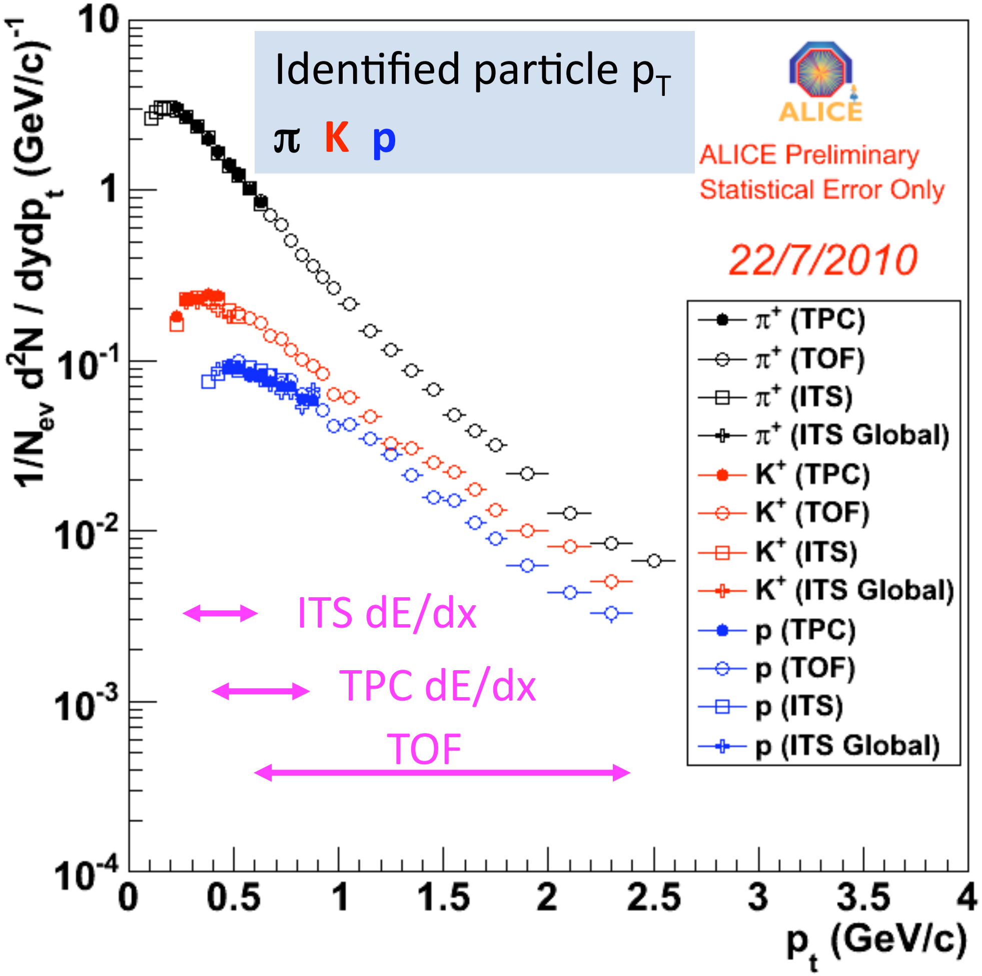


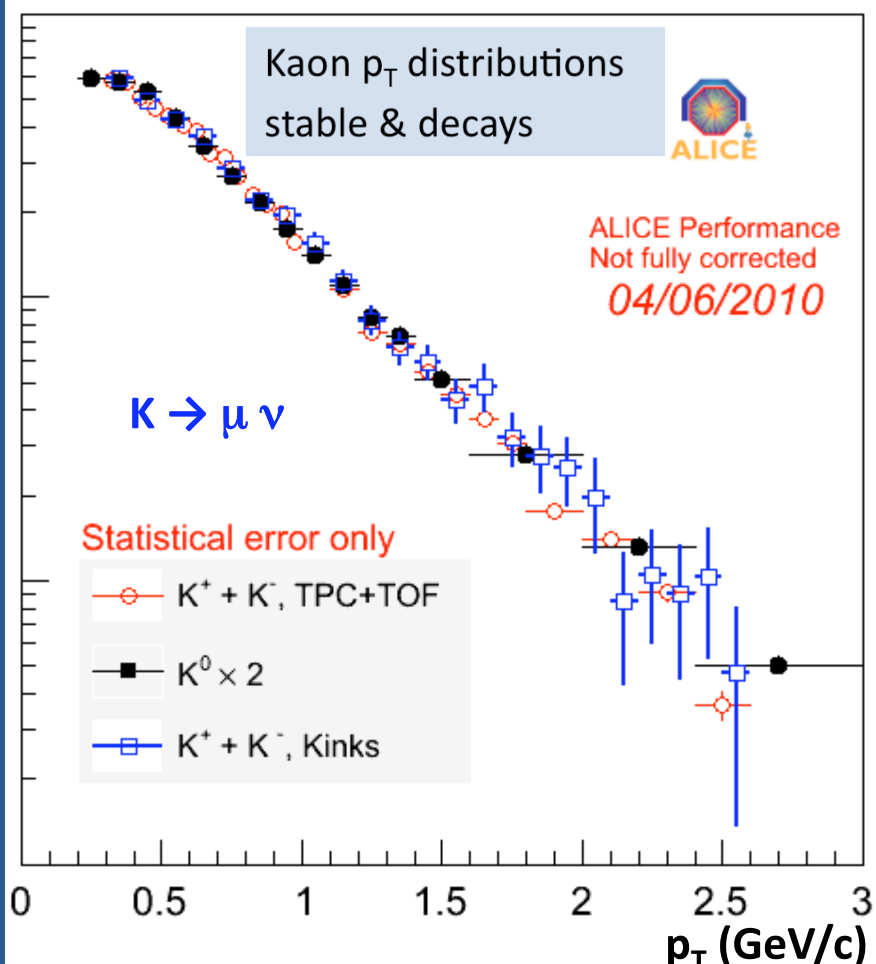
ALICE combines variety of different PID detectors and techniques.





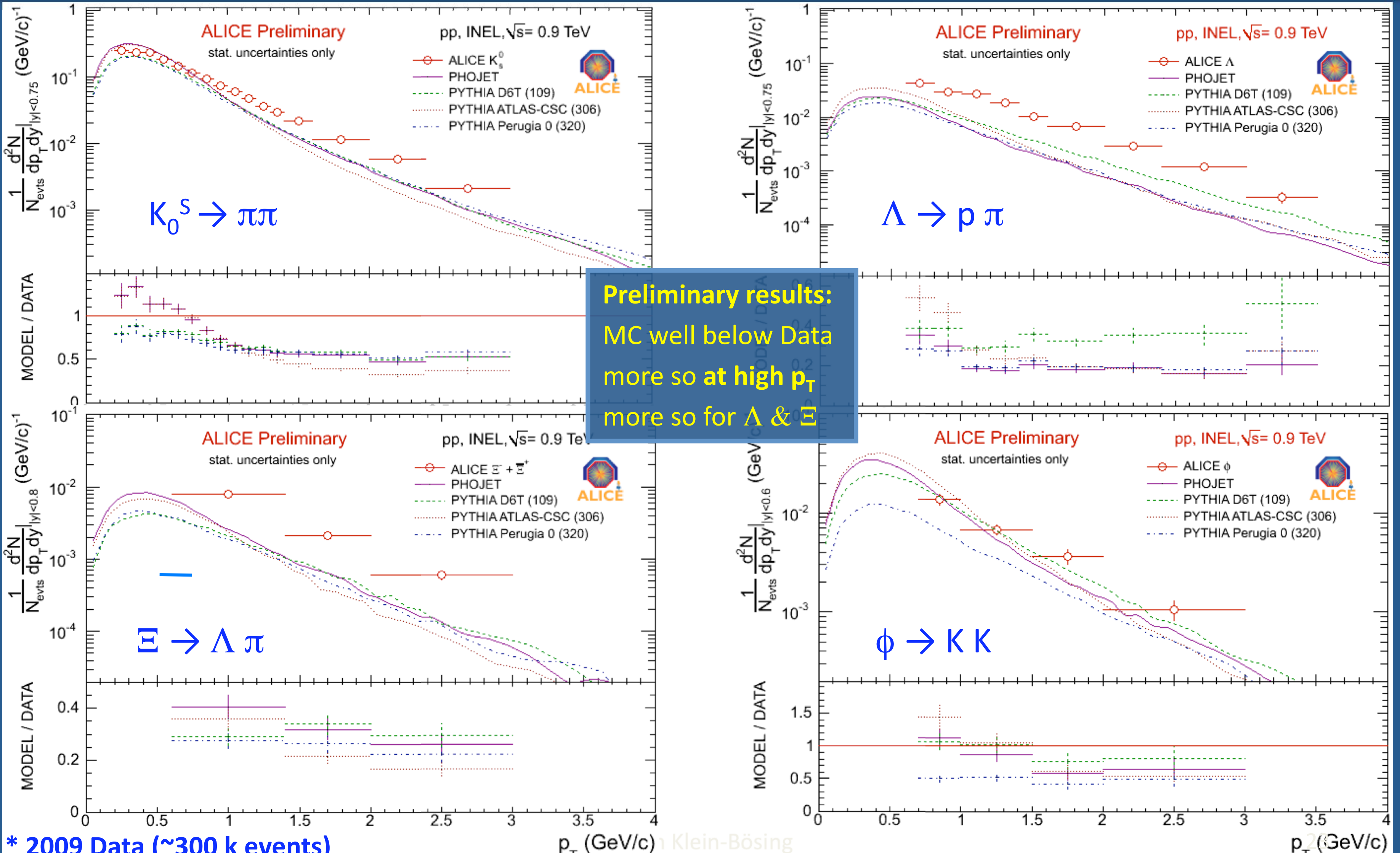
Identified Particles





Very good agreement between different methods.

Reconstructed Decays: K_0^S, Λ, Ξ, ϕ @ 900 GeV*



Preliminary results:

MC well below Data

more so **at high p_T**

more so for Λ & Ξ

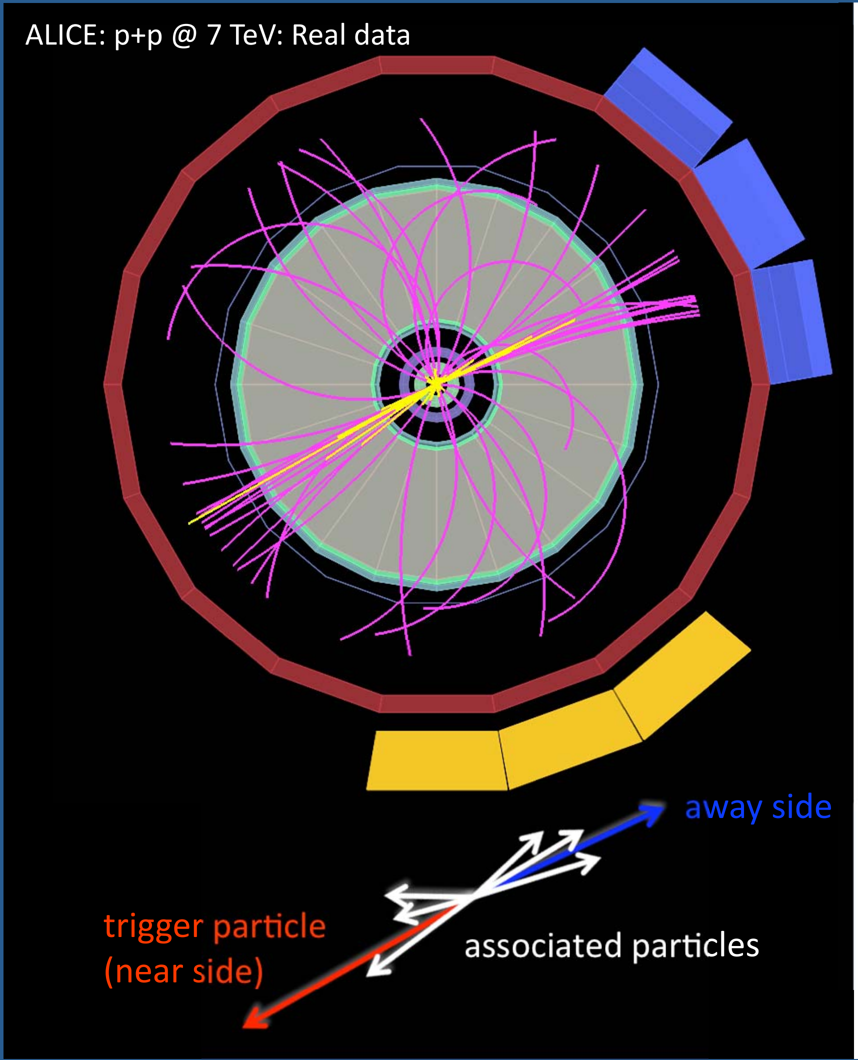
* 2009 Data (~300 k events)

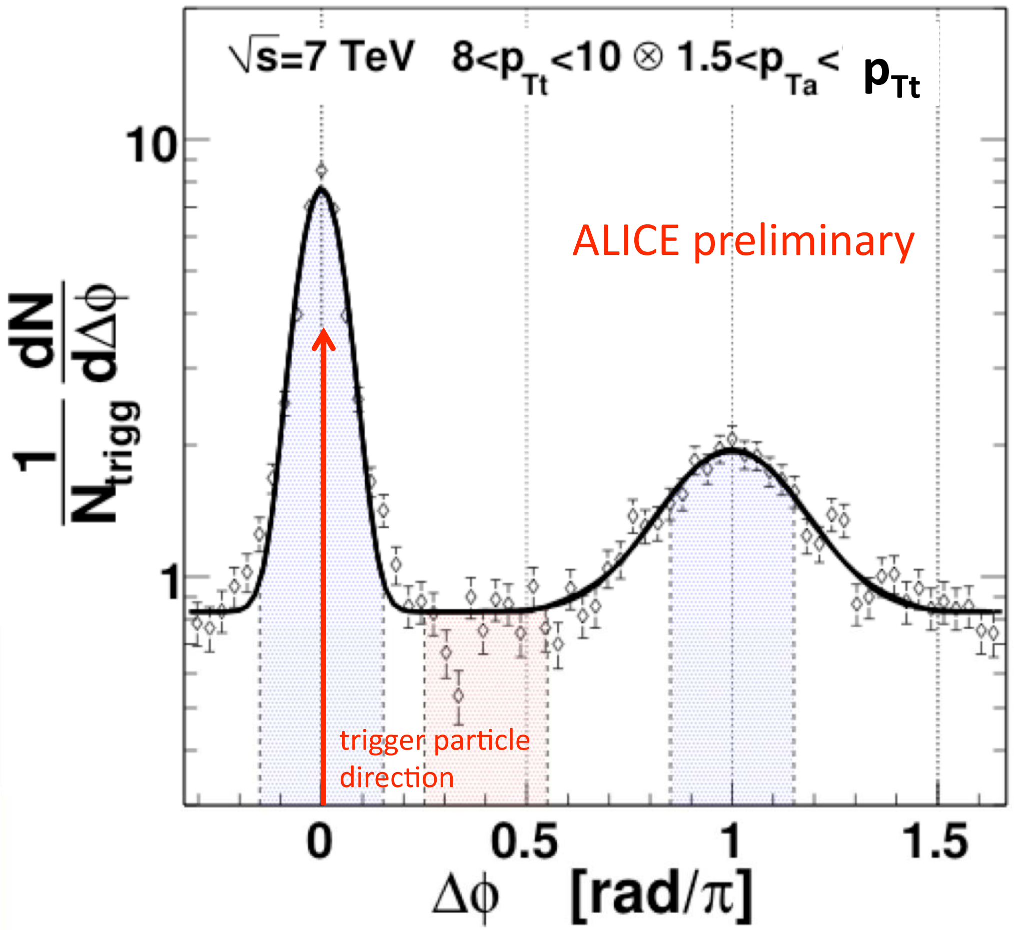
What we already learned from p+p

- The overall multiplicity is larger than expected
- Identified particles
  - MCs seem to underpredict strange particle production at high p_T
- Monte Carlo Generators have difficulties to describe soft and semi-hard region
  - Better tuning needed or qualitatively new physics missing?
- How are these observables influenced by jets?
  - Contribution of jet fragmentation to overall multiplicity
  - Total rate of jets, initial pQCD scattering should be well understood

Correlating Particles: Jet-like structures

Trigger Particle Correlations

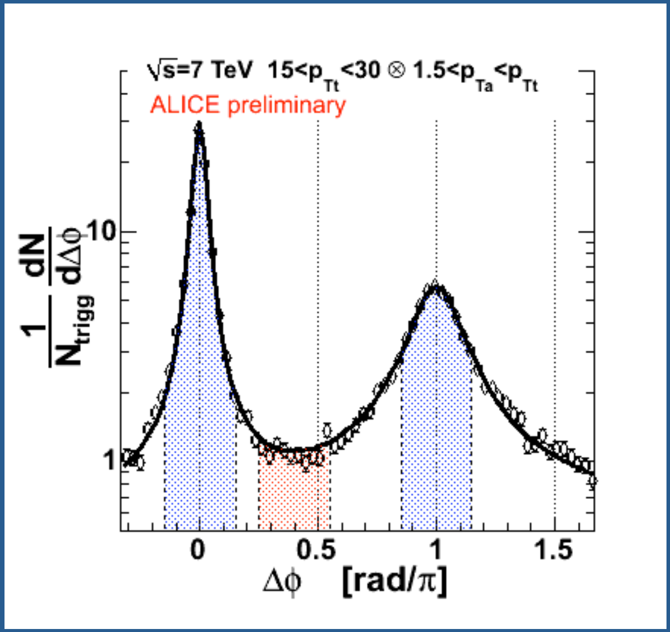


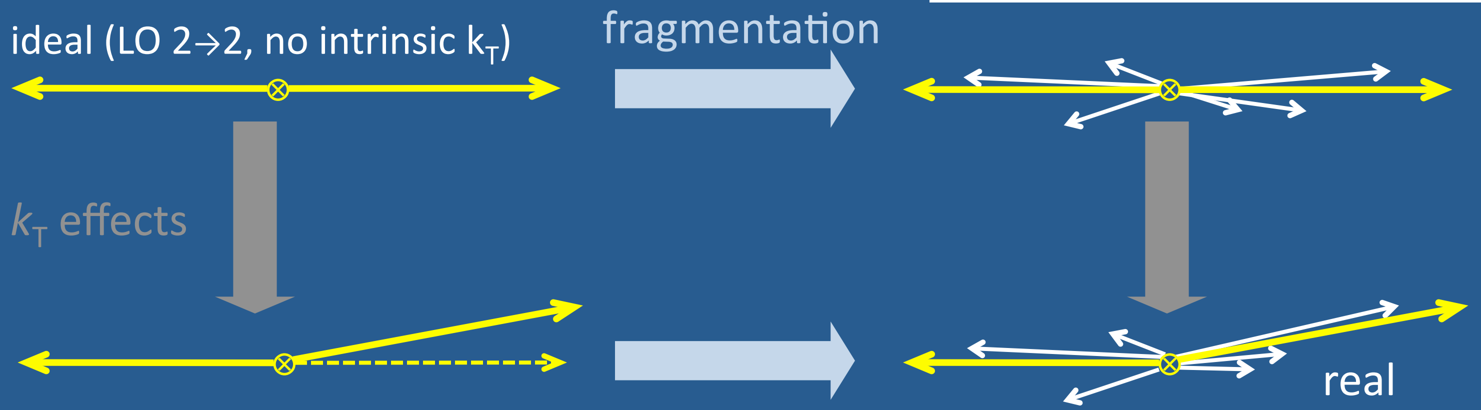


Clear back-to-back (di-jet) structure.
What does it tell us?

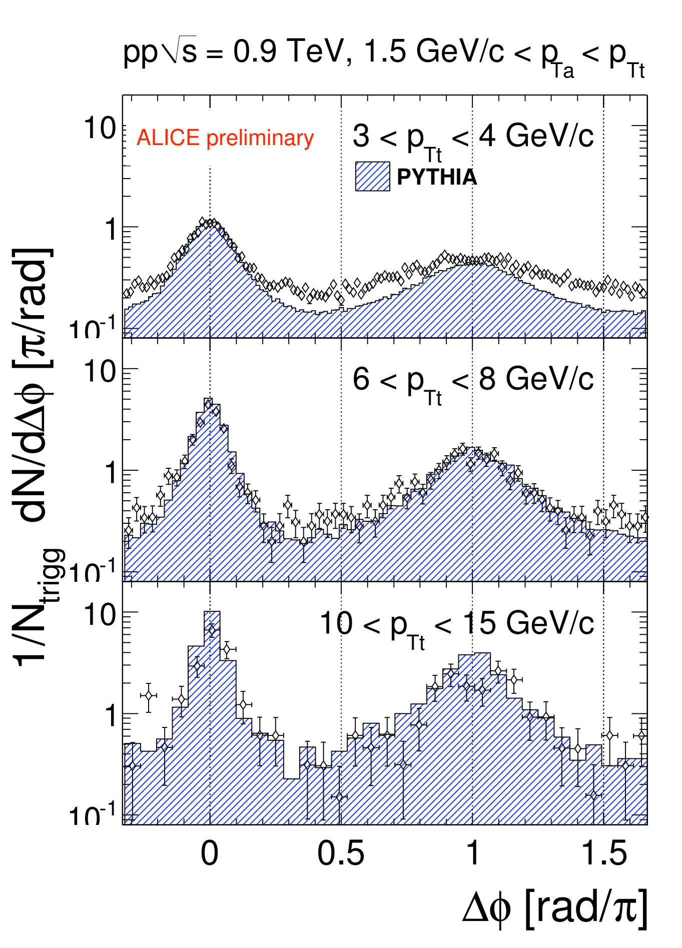
Particle Correlations: j_T and k_T

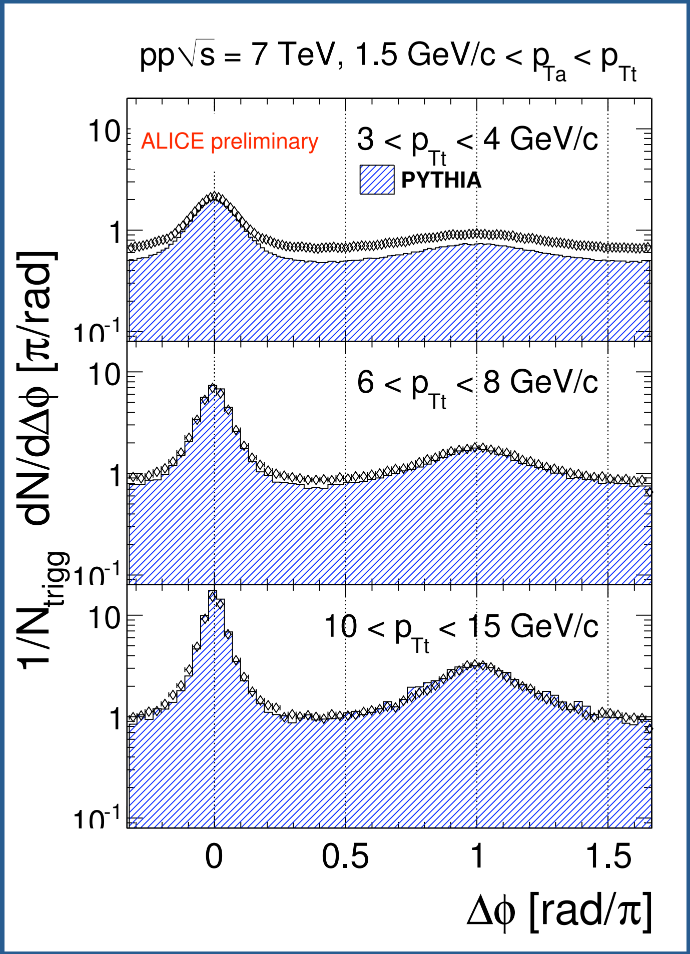
- Leading particle correlations
  - **Clear peaks at 180° in azimuth reveal di-jet structure**
- Near side width
  - Transverse momentum component due to fragmentation: $\mathbf{j_T}$
- Away side width
  - j_T plus
  - Momentum imbalance of scattered parton pair: $\langle \mathbf{p_{T,pair}} \rangle = \mathbf{\sqrt{2}} \langle \mathbf{k_T} \rangle$
  - Intrinsic momentum of partons in nucleons plus QCD effects (soft radiation and NLO): unequal momenta and acoplanarity





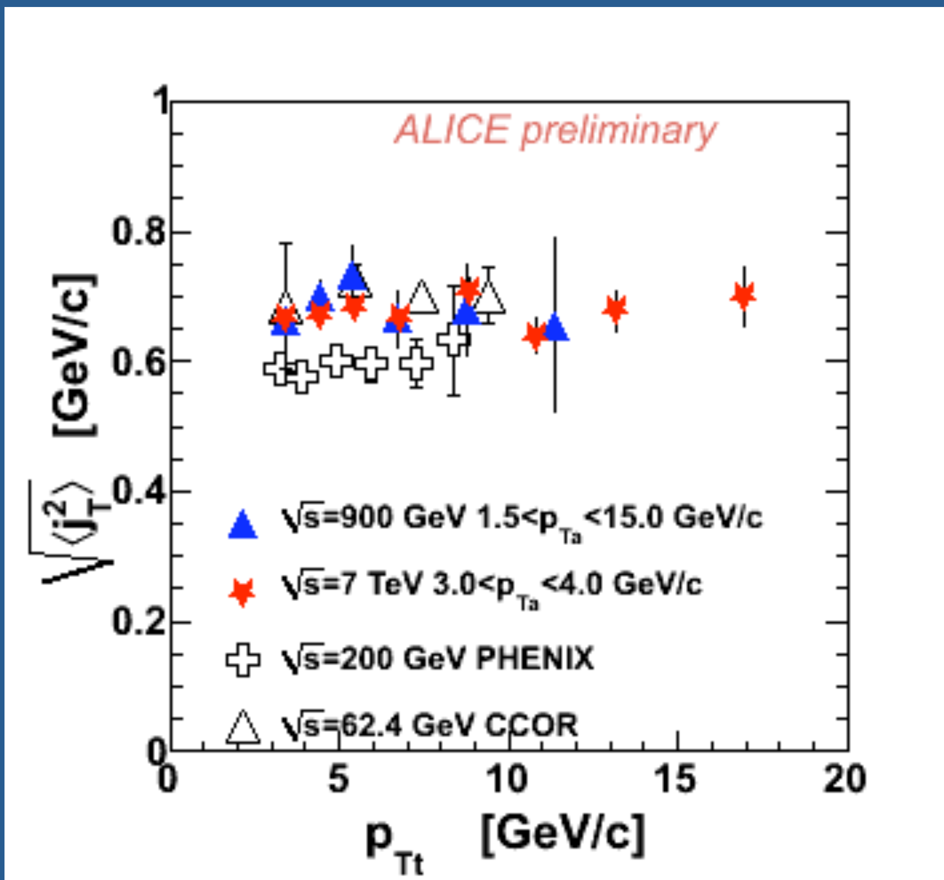
Correlation Functions
0.9 and 7 TeV





Provides access to jet-like properties down to low p_T (mini jets).
At low p_T overall event more spherical than expected (UE underestimated).

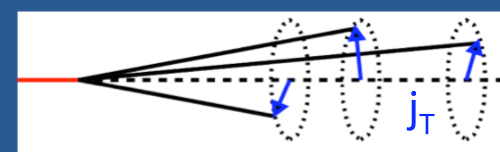
Fragmentation Effect: j_T



- Near side width $\Rightarrow j_T$

$$\sqrt{\langle j_T^2 \rangle} \approx \sqrt{2}\frac{p_{Tt}p_{Ta}}{\sqrt{p_{Tt}^2 + p_{Ta}^2}}\sigma_N$$

- Average transverse momentum of fragments relative to jet axis



- All measurements agree within errors
  - Systematic uncertainties not shown

Expected independence (universal fragmentation) confirmed over two orders of magnitude in √s.

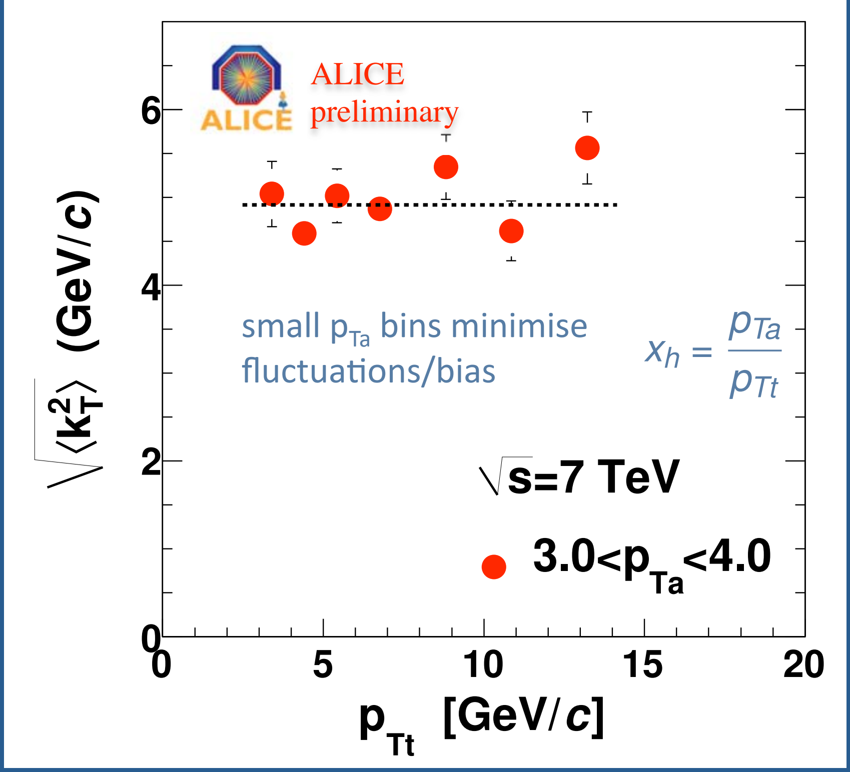
Partonic Momentum Imbalance: k_T

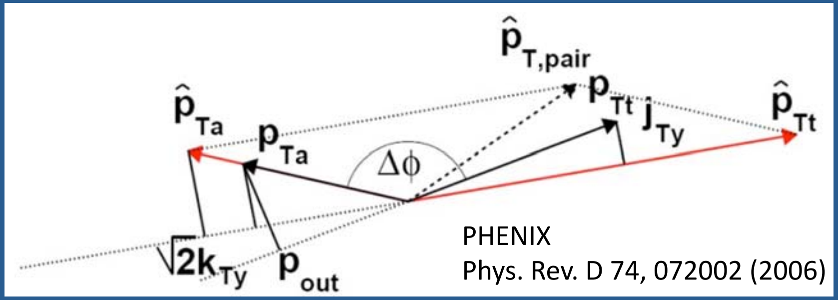
calculable

$$\frac{\langle z_t \rangle}{\langle \hat{x}_h \rangle}\sqrt{\langle k_T^2 \rangle} = \frac{1}{x_h}\sqrt{\langle p_{out}^2 \rangle - \langle j_{Ty}^2 \rangle (1 + x_h^2)}$$

partonic hadronic/measured

Only assumption in calculation: Shape of fragmentation function.





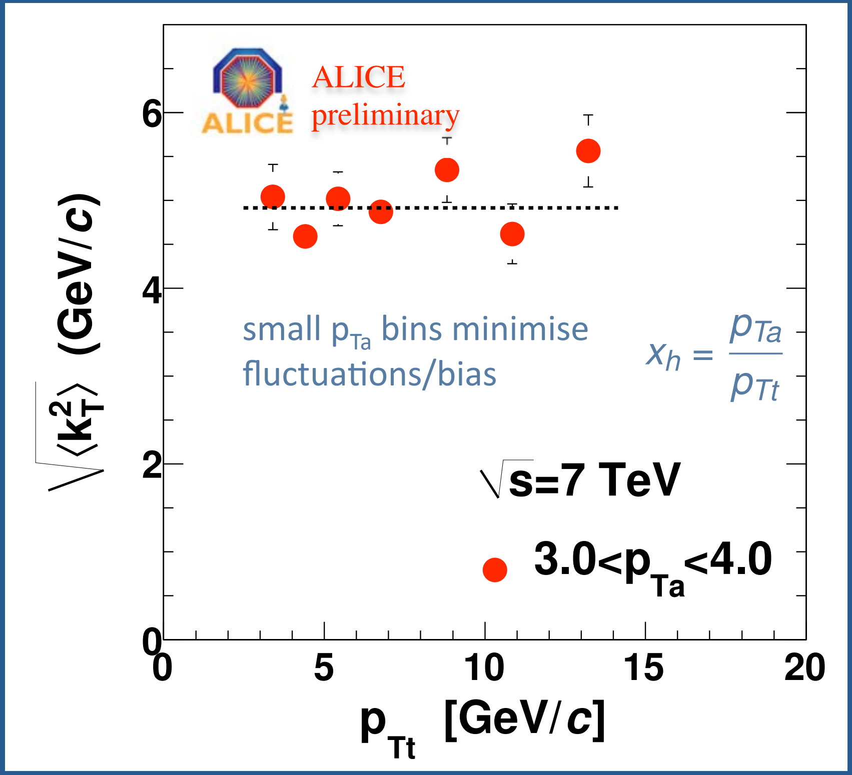
Event by event: $p_{out} = p_{Ta} \sin \Delta\phi$

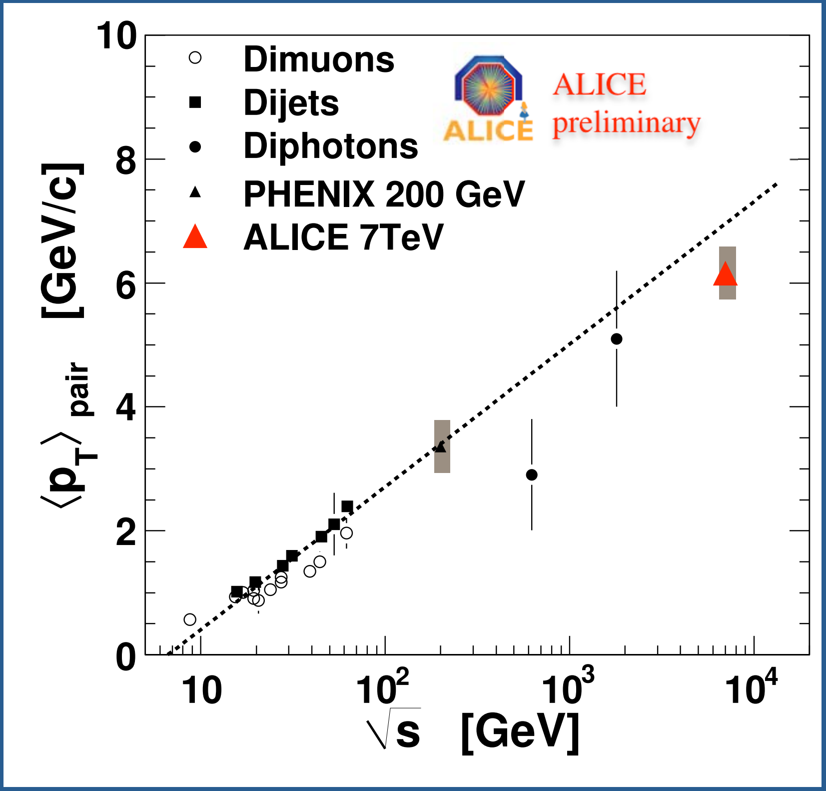
Partonic Momentum Imbalance: k_T

calculable

$$\frac{\langle z_t \rangle}{\langle \hat{x}_h \rangle}\sqrt{\langle k_T^2 \rangle} = \frac{1}{x_h}\sqrt{\langle p_{out}^2 \rangle - \langle j_{Ty}^2 \rangle (1 + x_h^2)}$$

partonic hadronic/measured



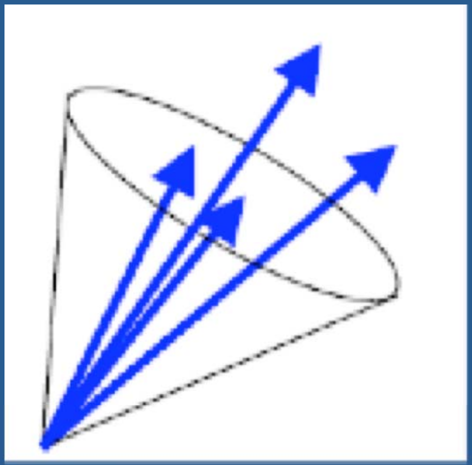


Confirmed increase of momentum imbalance of parton pair at a new √s.

Clustering Particles: Jets

Jet Finding in p+p (Example Cone algorithm)

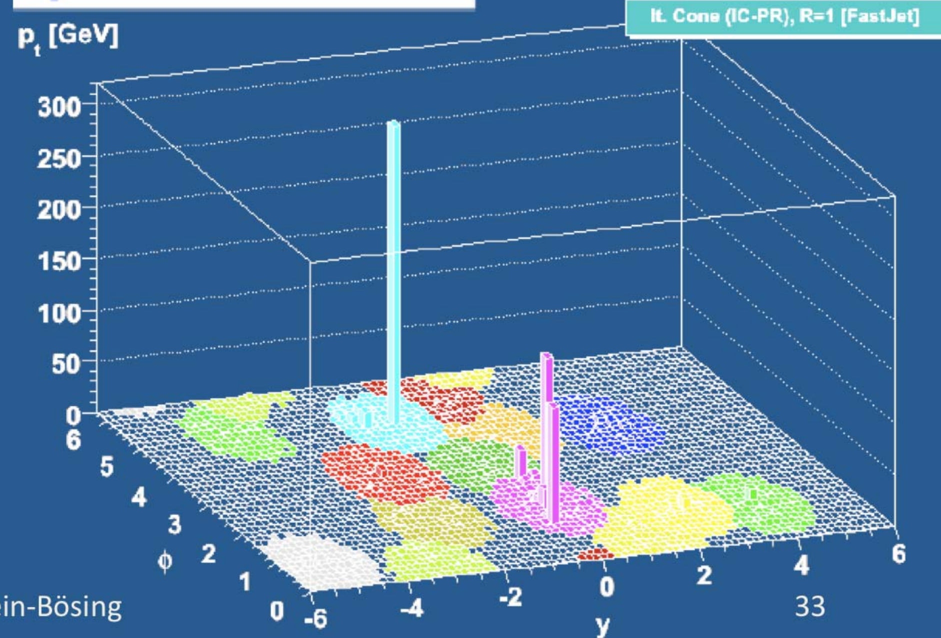
- Traditional choice in hadron collisions
  - Define η-ϕ grid
  - Search for regions of energy flow (cones) starting with a *seed*
  - Iterate until jet axis is stable
- Works because QCD only modifies energy flow on small scales
- Other class of algorithms
  - Sequential recombination/k_T algorithm: traditional choice in e^+e^-
- Corrections are needed to account for the **underlying event**



Combine particles in a cone with radius

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$

Typical choice:
***R* = 0.7**



Year-1 Jet Finding with ALICE

- Based on central tracking detectors
  - Only jets from **charged particles**
  - EMCAL/PHOS
    - cross-check for neutral jet energy fraction in limited acceptance
    - Jet energy scale check via γ + jet

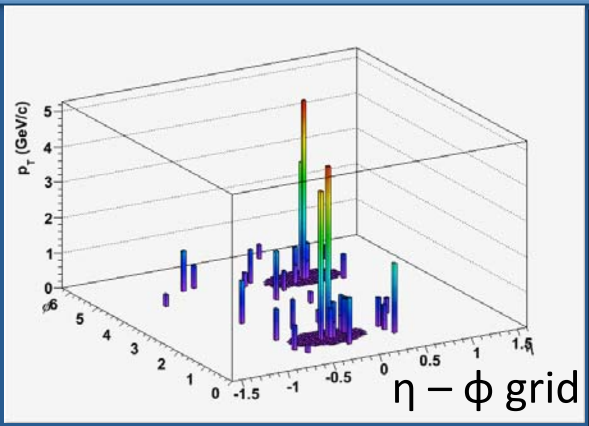
- Cone size/resolution parameter $R = 0.4$
  - Comparison to Pb+Pb
  - Maximum efficiency of central barrel $|\eta| < 0.9$

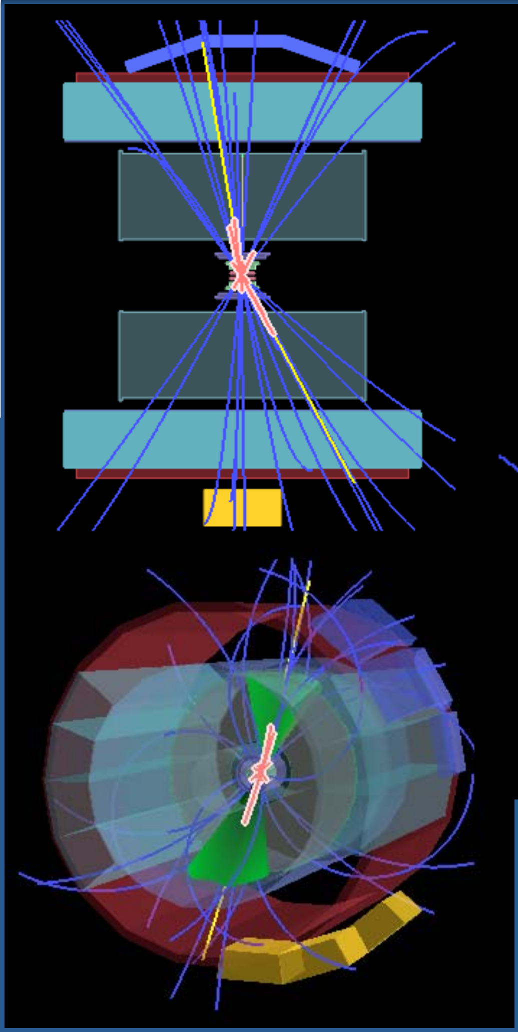
Current limitation to charged particles reveals sensitivity to fluctuations/ fragmentation

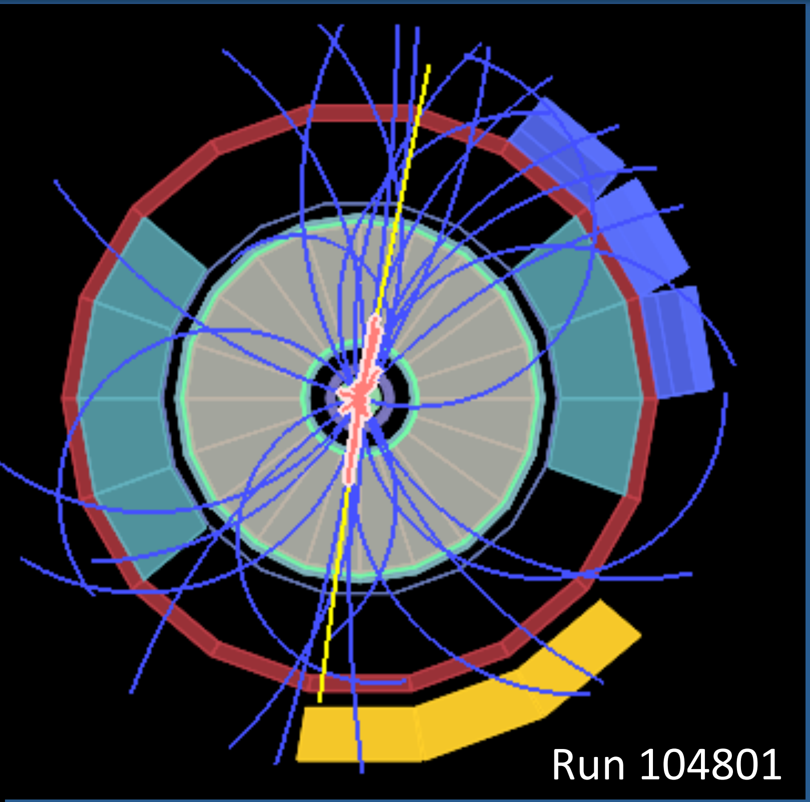
- Jet finders
  - UA1 Cone Algorithm
  - FastJET suite (k_T, anti-k_T, SISCone)
  - Deterministic Annealing

Important cross-check of jet finder systematics

First Di-*jets* @ 0.9 TeV







Reconstructed Jets with UA1 Cone R = 0.4:

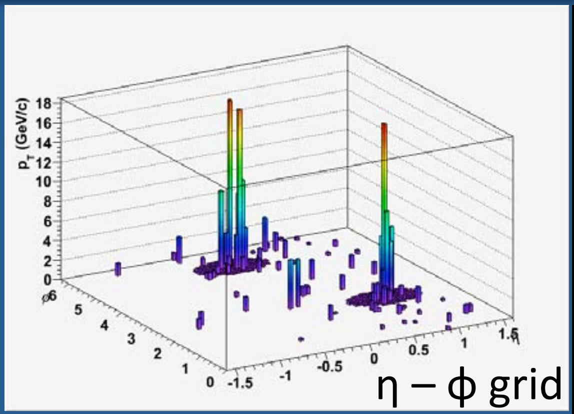
Jet 1: η = -0.17, ϕ = 78°, **p_T = 11.2 GeV**, Tracks 5

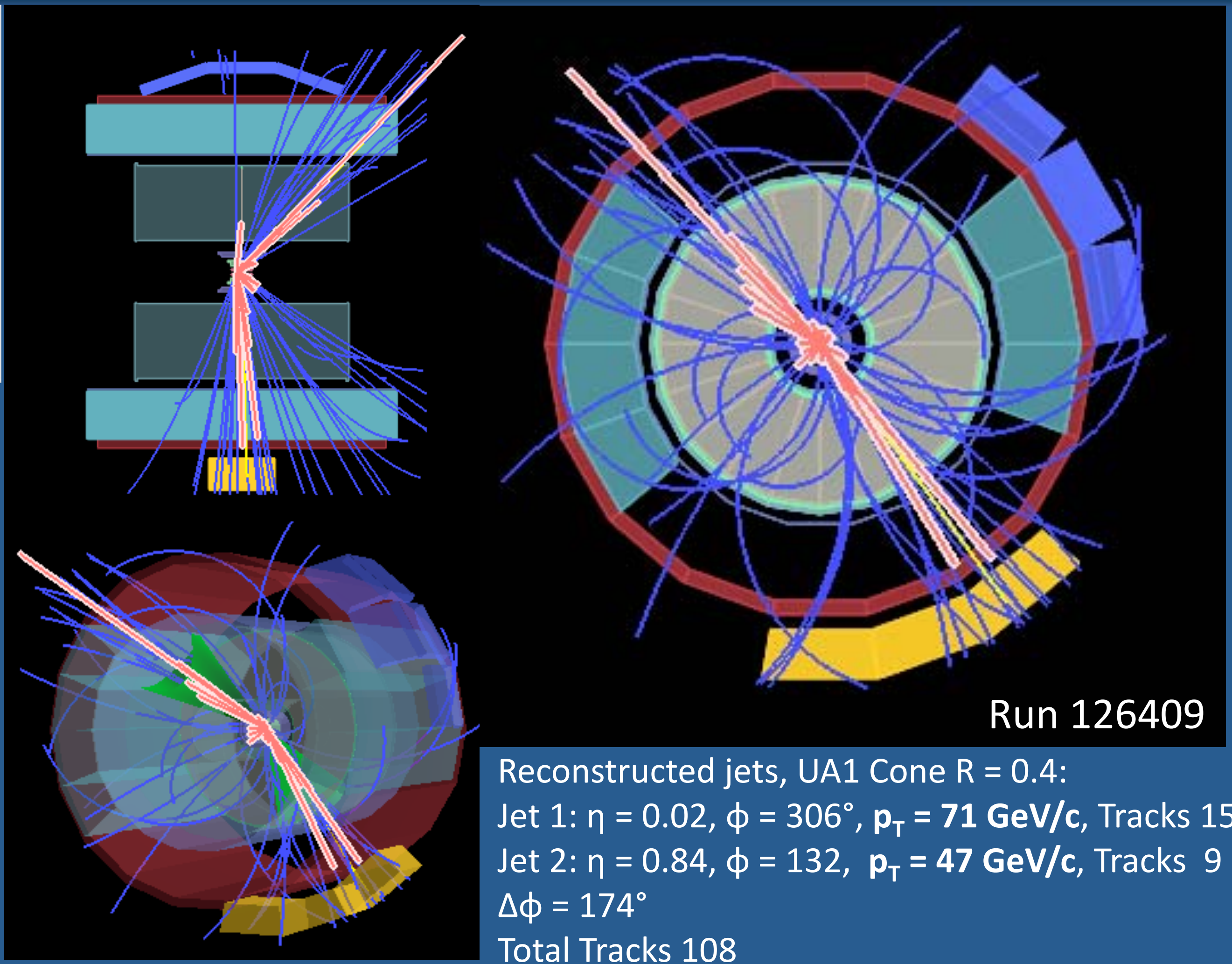
Jet 2: η = 0.52, ϕ = 262°, **p_T = 9.3 GeV**, Tracks 4

Δϕ = -184°

Total Tracks 61

Di-jets @ 7 TeV





Reconstructed jets, UA1 Cone R = 0.4:

Jet 1: η = 0.02, ϕ = 306°, **p_T = 71 GeV/c**, Tracks 15

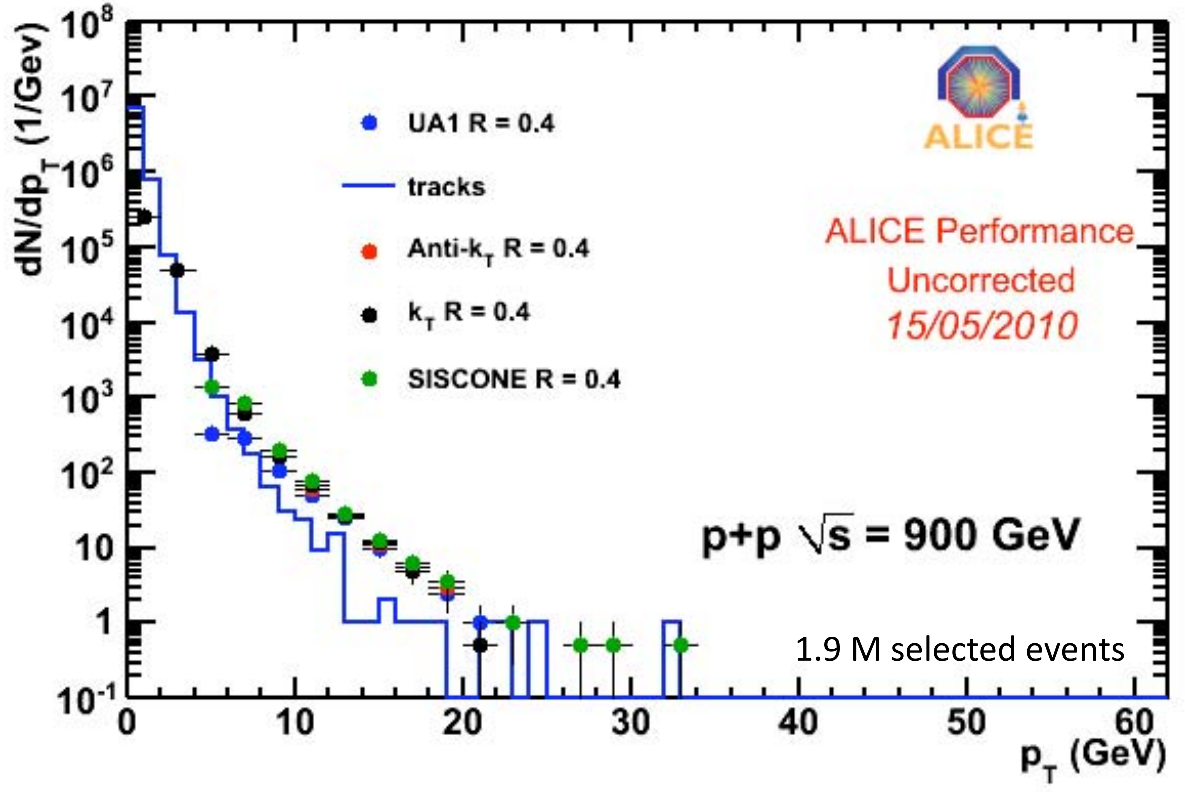
Jet 2: η = 0.84, ϕ = 132, **p_T = 47 GeV/c**, Tracks 9

Δϕ = 174°

Total Tracks 108

Raw *Jet* Spectrum p+p @ 0.9 TeV

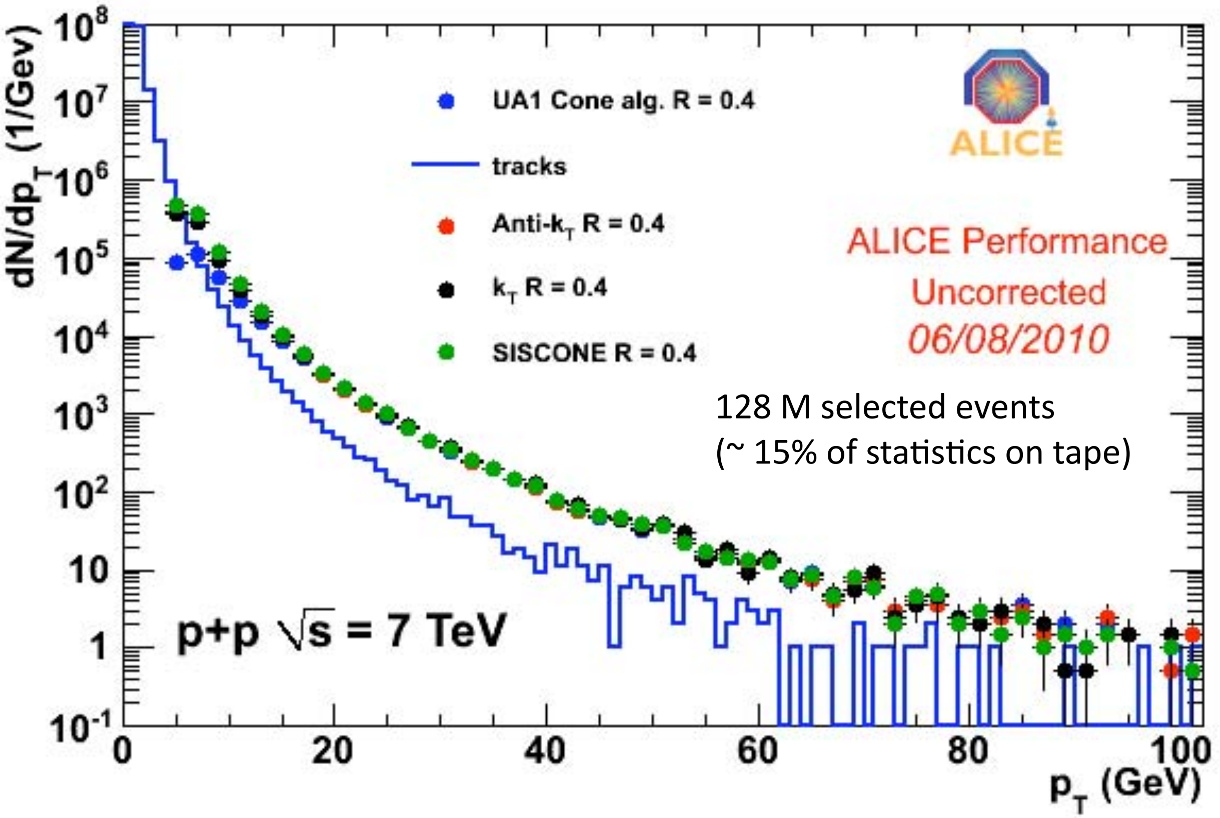
Jets within |η| < 0.5, Tracks within |η| < 0.9



Excess above single particles between 10 and 15 GeV.

Raw Minimum Bias Jet Spectrum p+p @ 7 TeV

Jets within |η| < 0.5, Tracks within |η| < 0.9



Jet spectrum with charged particles alone safely reconstructed out to 80 GeV.
All jet finders consistent above 20 GeV.

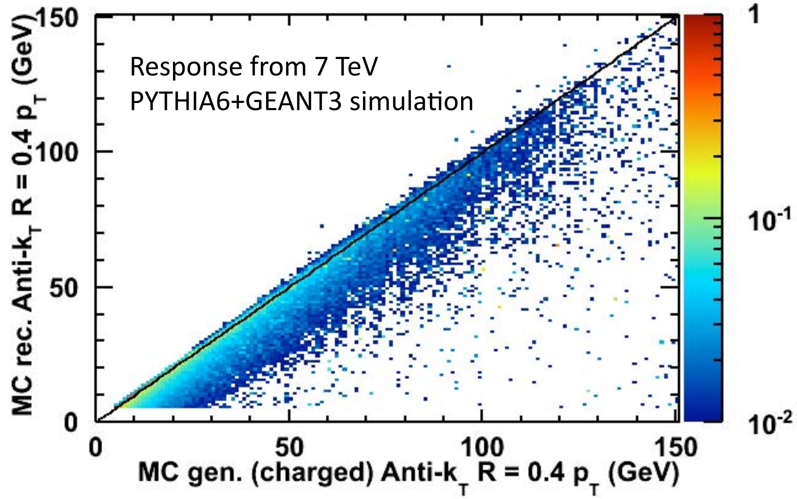
ALICE Jet Response

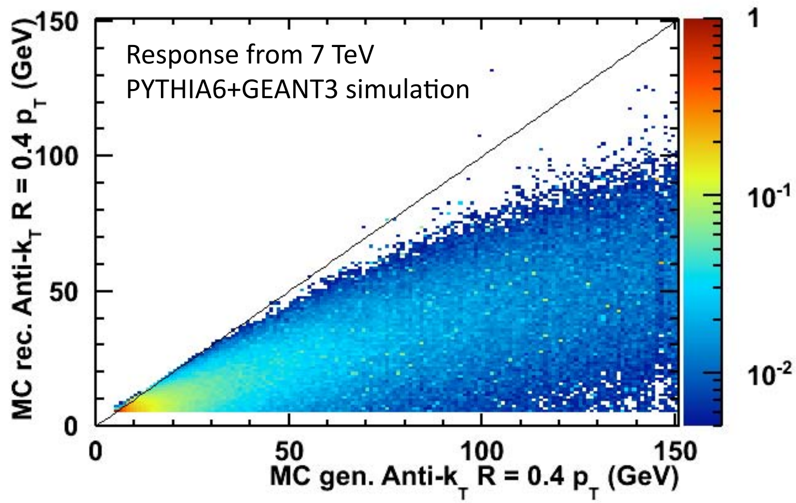
- Encoded in matrix, used for unfolding:

$$p_{T,rec} = R_{rec,gen} \cdot p_{T,gen}$$

- Two corrections possible
  - Charged track jet → charged particle jet
    - Determined by detector/instrumental effects
    - **Tracking resolution**, efficiency, cuts
  - Charged track jet → all particle jet
    - Dominated by charged/neutral fluctuation
    - Shift and smear of jet energy scale
    - Depends on fragmentation and jet composition

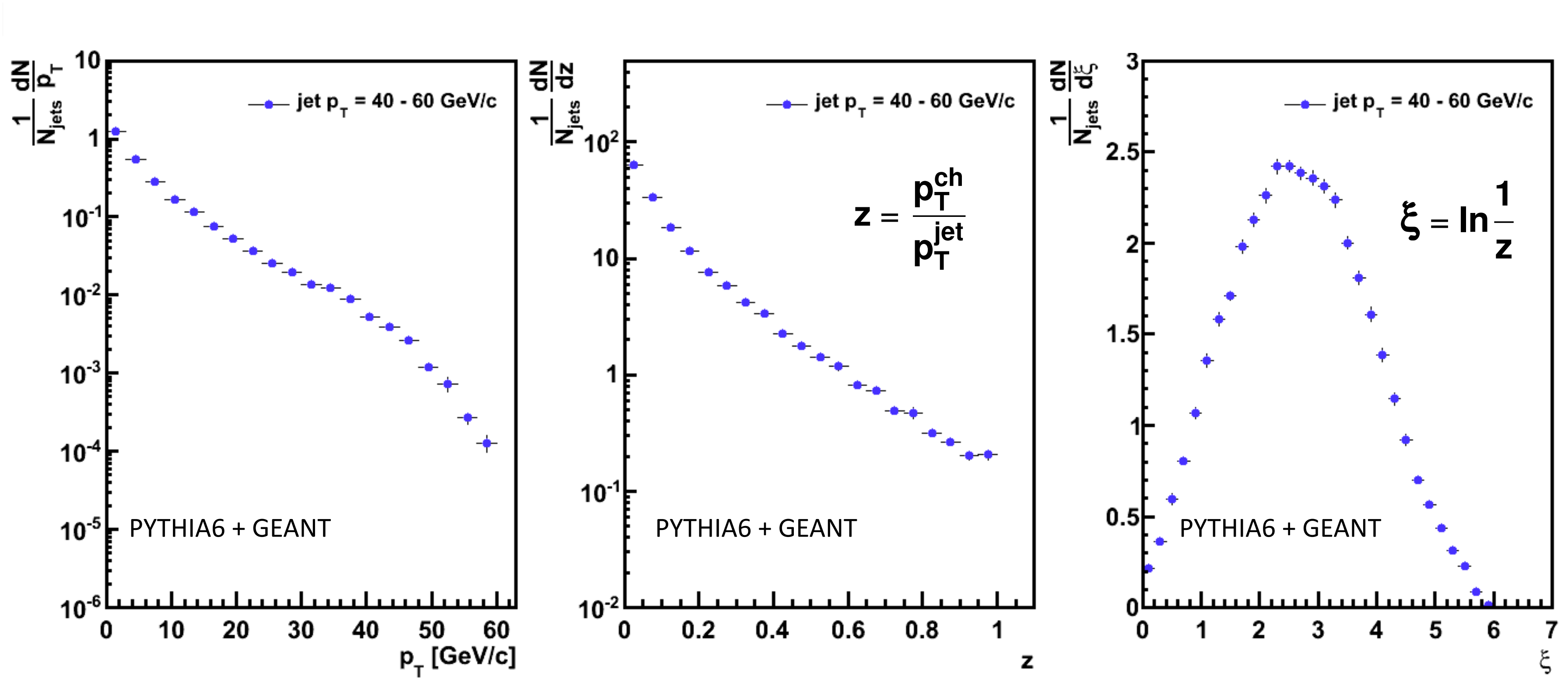
Simulations show a good response to charged fraction of the jet. Currently finalizing corrections.





Taking the jets apart again: Momentum Distributions

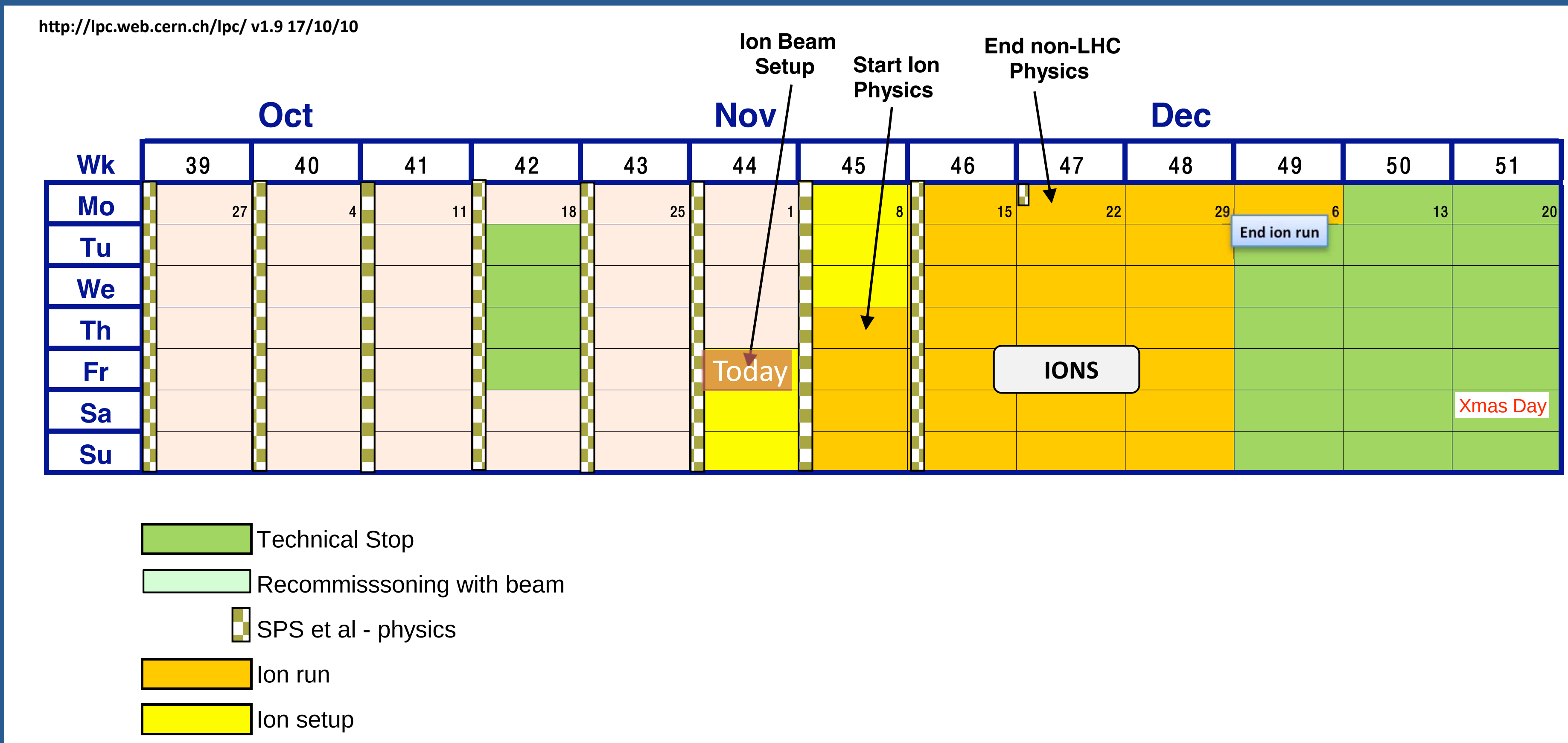
Momentum Distributions for jets (p_T = 40 – 60 GeV/c) from charged particle tracks: Three representations



See posters: B. Bathen, Oliver Busch

Will provide test of low p_T fragmentation processes (supplemented with PID) and serve as reference for heavy-ion data.

LHC Schedule 2010: What's Next?

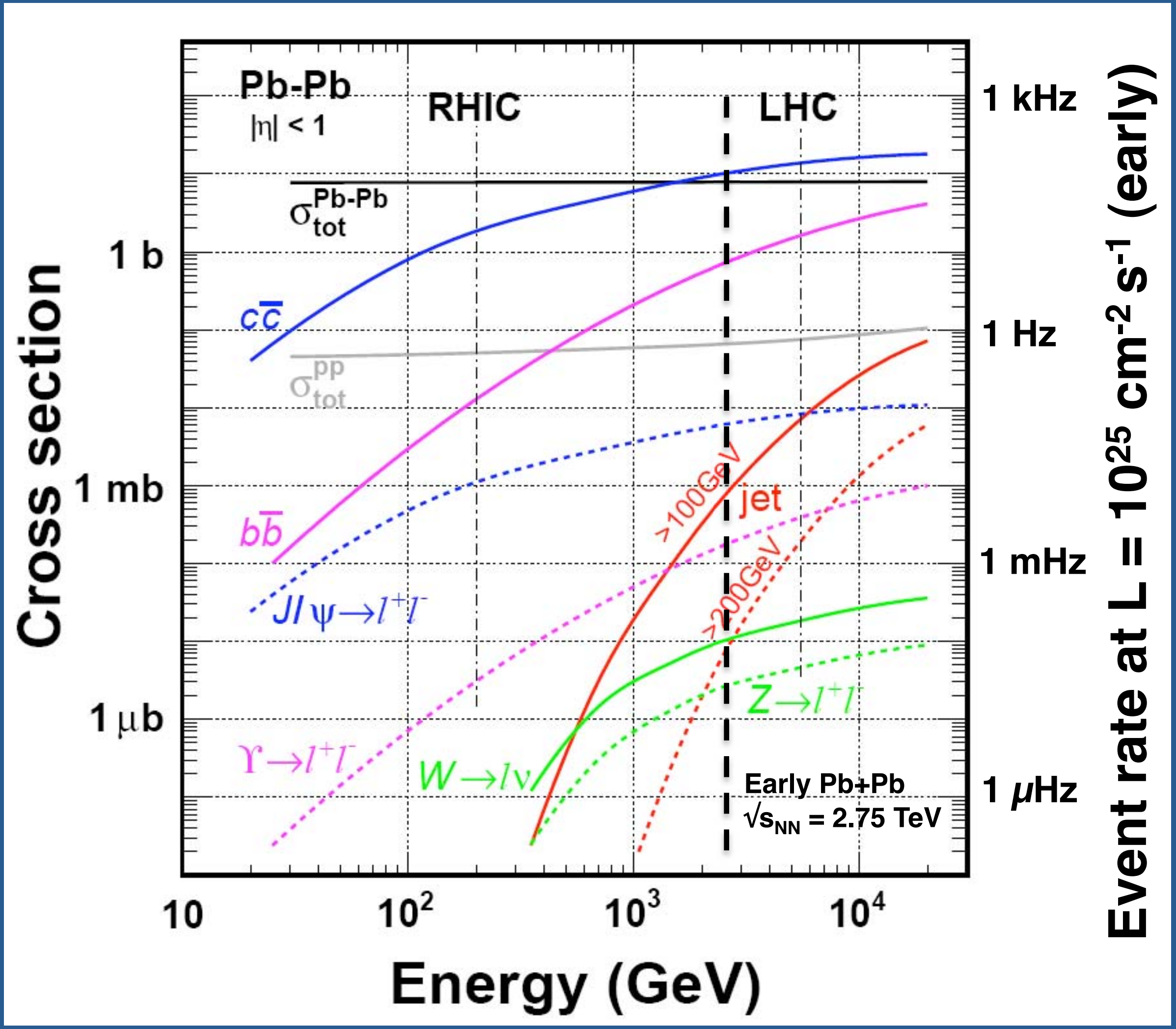


LHC Schedule 2010: What's Next?

1st Circulating heavy ion beam yesterday evening … (75 turns)

Collimation (RAMP)	1 (non colliding)	1	Ramp: measure to verify hierarchy appropriate for ion beams. test predictions Loss maps	COLL	RA, DW, GV, GB	FRI N
LBDS	1 (non colliding)	0.25	Asynchronous beam dump	ABT	BG	FRI N
Setup for collisions	2 (colliding)	2	Squeeze, find collision, and transition to zero real crossing angle in ALICE, CMS & ATLAS. LHCb separated, squeezed.	OP		SAT M,A
			Collimation setup.	COLL	RA, RB, DW, MC, GB	
Collimation	2 (colliding)	1	Loss maps	OP	GB	SAT N
LBDS	2 (colliding)	0.25	Asynchronous dump	ABT	BG	SUN M
First collisions + PHYSICS	2 colliding	1 or 2	Ramp with two beams, squeeze, checks, Stable beams.			SUN M
Increase intensity (1)	17	1 or 2	Increase bunch number to 17 (16 colliding in IP1,2,5 + 1 probe)			
Increase intensity (2)	120	1	Increase bunch number to 128			
Physics	120		Parasitic measurements during physics (luminosity evolution, BFPP, etc, ...) to test models and prepare future runs			

Early Heavy-Ion Running



Early heavy-ion running ≈ 1% of nominal luminosity (≈ 1 ×10^{25} $cm^{-2}s^{-1}$/10^{27} $cm^{-2}s^{-1}$)

First high p_T physics program:
Single particle spectra/ particle correlations:
p+p vs. Pb+Pb,
centrality dependence.
One 100 GeV jet every 100 s.

Conclusions

- Hard probes allow for a deep look into extreme matter created in heavy-ion collisions
  - Reconstruction of full jets complementary to single particle measurements
- Detailed characterization of first p+p data at 900 GeV and 7 TeV ongoing
  - Already several papers published, more coming soon
  - Important contributions to p+p phenomenology, mini-jets and jet hadronization
  - Baseline for Pb+Pb
- Awaiting first Pb+Pb @ $\sqrt{s} \approx 2.75$ TeV in the next days:
  - Jet modification measurement with single particles and correlations
  - Final optimization of jet finding
  - First reconstructed jets in heavy-ion collisions at the LHC

Papers:

Charged particle multiplicity	900 GeV	EPJC **65** (2010) 111
	900 GeV & 2.36 TeV	EPJC **68** (2010) 89
	7 TeV	EPJC **68** (2010) 345
p_T distribution	900 GeV	PLB **693** (2010) 53
Bose-Einstein correlations	900 GeV	PRD **82** (2010) 052001
Antiproton/proton	900 GeV & 7 TeV	PRL **105** (2010) 072002

Posters:

Measurement of π^0 and η mesons with photon conversions in ALICE in p+p collisions at $\sqrt{s}$ = 7 Te

Method to Extract Direct Photons via Conversions in p+p Collisions at 7 TeV with ALICE

$J/\psi \rightarrow e^+e^-$ measurement in pp collisions at $\sqrt{s}$ =7 TeV with the ALICE detector

D^{*+} and D^0 reconstruction in ALICE

Charged particle momentum distribution in Jets in ALICE

Electron identification in the ALICE experiment in p+p collisions at $\sqrt{s}$ = 7 TeV at the LHC

Electrons from heavy flavour decays with ALICE at the LHC

Beauty and Beauty jet measurement with ALICE at the LHC

Thank you

A Simulation (still…)