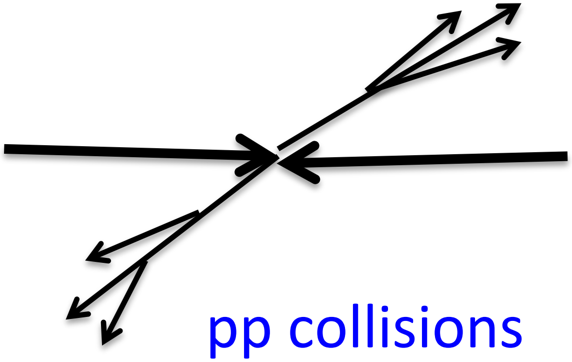
Jets in ALICE: from vacuum to high temperature QCD

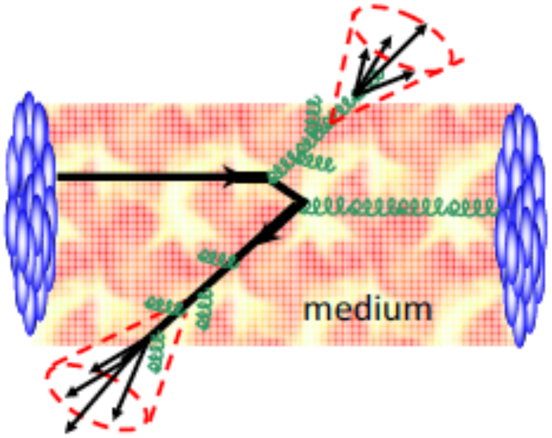
Leticia Cunqueiro (CERN) for the ALICE Collaboration

PH-LHC seminar
2014, December 16th

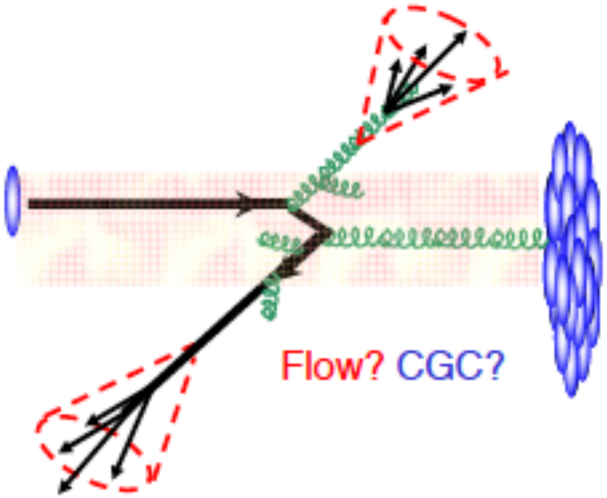
Jets in pp, p-Pb and Pb-Pb



pp collisions



AA collisions



pA collisions

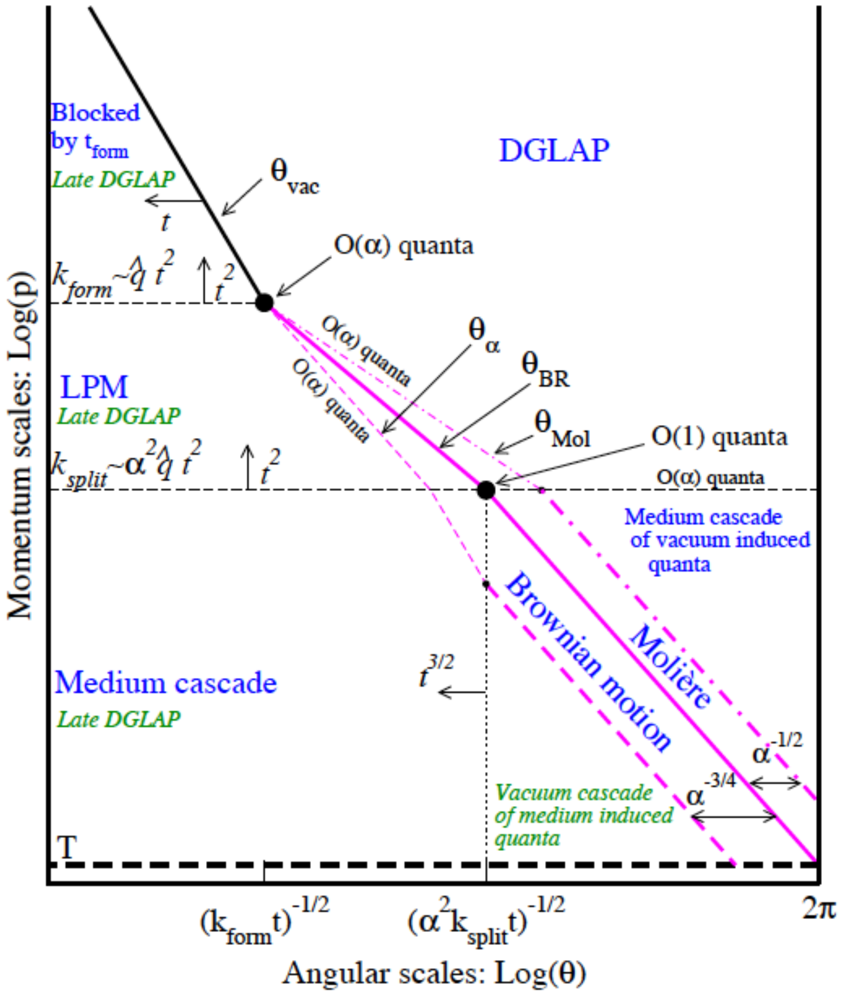
-The hard scattered parton is produced in short time scales 1/Q

-The parton traverses medium and interacts with its constituents

-The parton looses energy through elastic scattering and gluon radiation→ jet quenching →modified FF

Jet quenching

Unified map of the physics underlying jet quenching



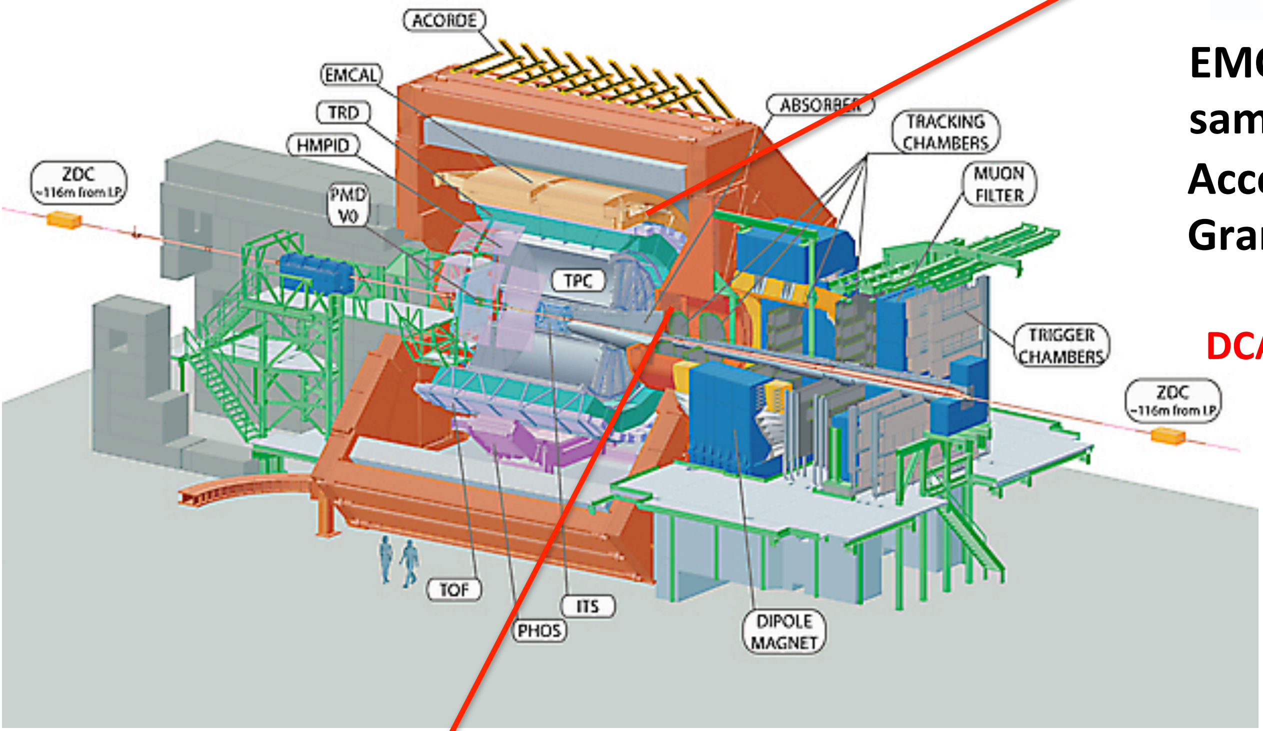
[Kurkela and Wiedemann, arXiv:1407.0293v1]

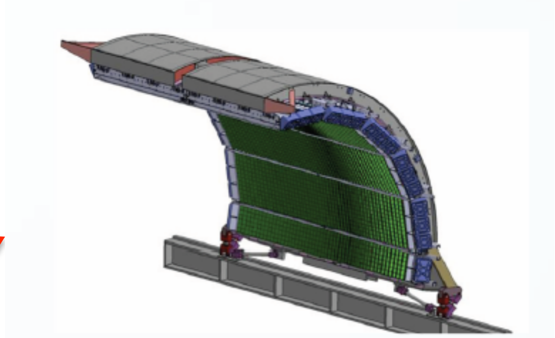
Different physics depending on region of phase space:

- Vacuum DGLAP evolution
- Medium-induced gluon emission, LPM interference region
- Moliere or large angle scattering
- …

Measure **medium modifications of the jet shower** and relate them, through theory, to the **medium temperature**, **small angle scattering properties** (qhat, the average transverse momentum transferred from the medium to the parton per unit path legnth) or the **quasi particle content of the medium** (weak vs strong)

Jets in ALICE





EMCal is a Pb-scintillator sampling calorimeter
Acceptance: $|\eta|<0.7$, $1.4<\phi<\pi$
Granularity: $\Delta\eta=\Delta\phi\sim0.014$

DCAL: calorimetry extension in ready for Run2

Neutral constituents

$|\eta|<0.9$, $0<\phi<2\pi$
TPC: gas drift detector
ITS: silicon detector

Charged constituents

JET

Jets in ALICE

Input: -Tracks ($p_T > 0.15$ GeV), Calorimeter clusters ($E_T > 0.3$ GeV)

Jet Finding: -anti-k_T algorithm from FastJet package *[Eur.Phys.JC72(2012)1896]*
-boost invariant p_T recombination scheme
-resolution parameter R=0.2, 0.3, 0.4 & 0.6

Average background contamination is corrected on an event-by-event basis using area based method [*Phys.Lett.B659 (2008) 119-126]*

*Area correction for sparse p-Pb *[derived from arXiv:1207.2392]*

Removal of the combinatorial background in Pb-Pb

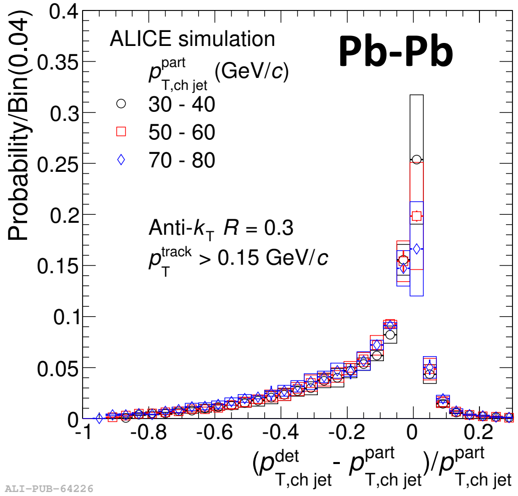
-Jet by jet basis: -jet area cuts
-minimum jet p_T cut-off
-requirement of a jet constituent above some p_T

-Ensemble basis: -via hadron-jet correlations

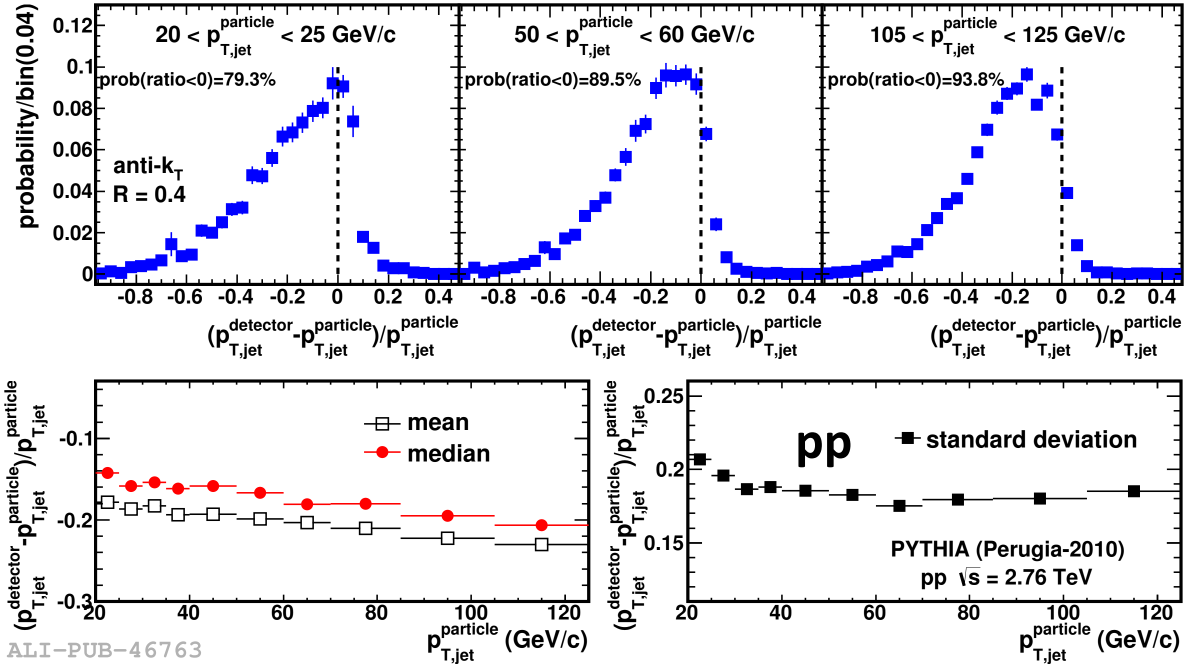
Instrumental response and residual background fluctuations are corrected via unfolding using several algorithms such as Bayesian, SVD and χ^2

Instrumental response

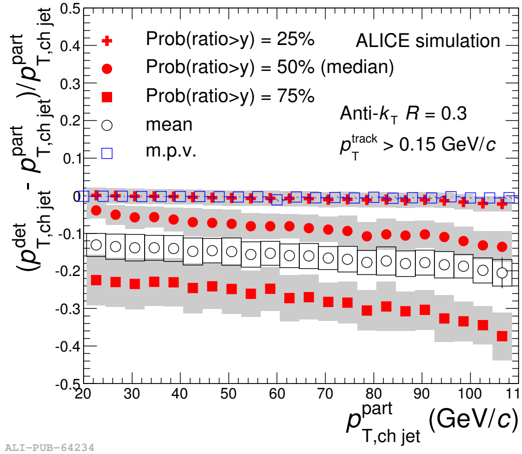
Track jet response



Full jet response



[ALICE, PLB722 (2013) 262]



[ALICE, JHEP03(2014)013]

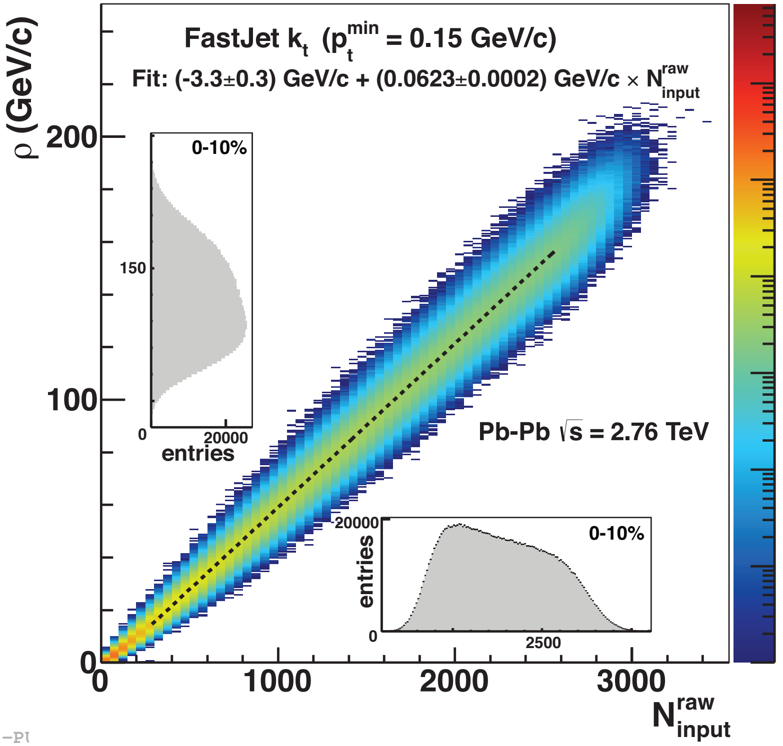
Shift of the Jet Energy Scale (JES) ~20%

JES uncertainty is dominated by tracking efficiency uncertainty and is ~5%

JER (instrumental jet energy resolution) ~14-19% with mild jet p_T and R dependence

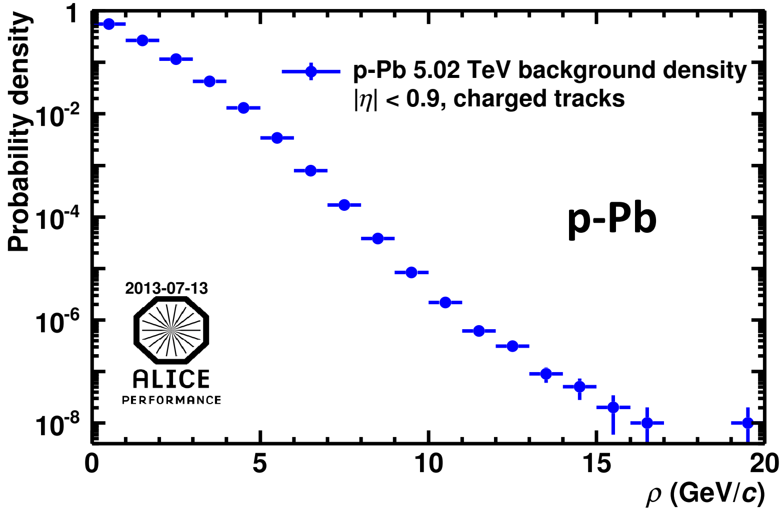
Background response: average correction

Pb-Pb



ALI-PI

$$\Delta p_T^{jet} \propto R^2$$



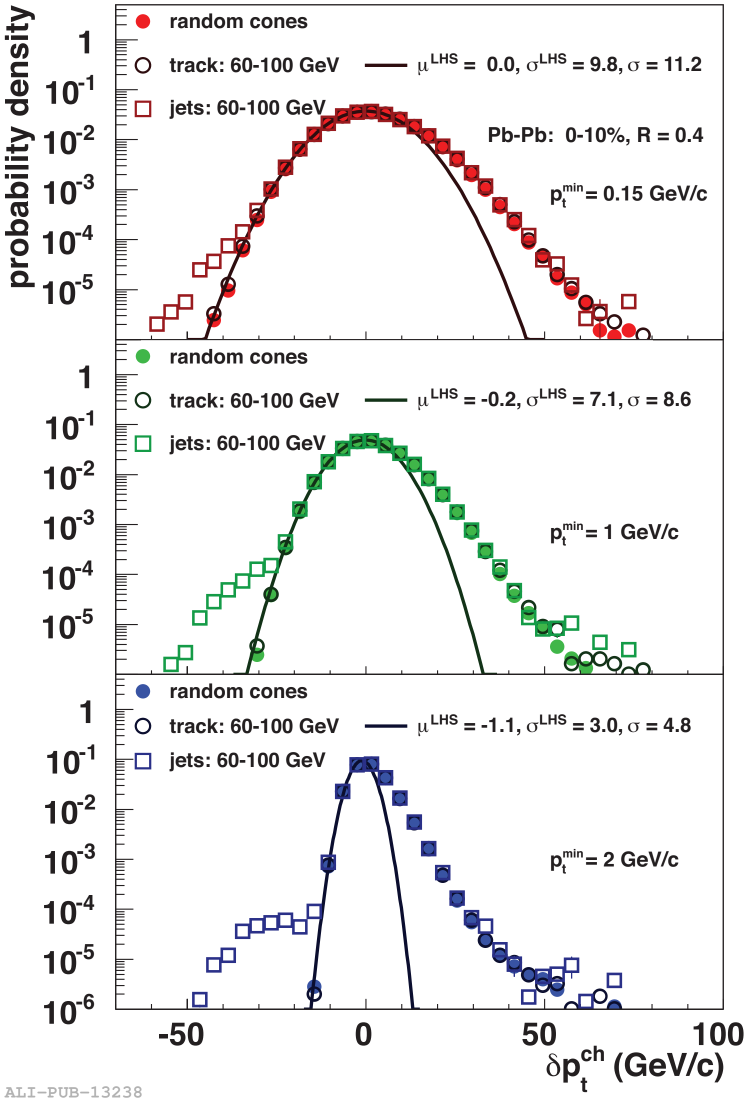
ALI-PERF-53829

$$\rho = \mathrm{median}\left\{\frac{p_{\mathrm{T,jet}}^{\mathrm{reco,i}}}{A_{\mathrm{jet}}^{\mathrm{i}}}\right\}$$

$$p_{\mathrm{T,jet}}^{\mathrm{raw,i}} = p_{\mathrm{T,jet}}^{\mathrm{reco,i}} - \rho \cdot A_{\mathrm{jet}}^{\mathrm{i}}$$

- **Area-based techniques to measure the average background density**
- **Robust median calculation of the p_T per unit jet area of k_T clusters** **(empty space corrections in p-Pb)**
- **Event-by-event, jet-by-jet, subtraction of the average background energy**

Background response: region-to-region fluctuations



[ALICE, JHEP03(2012)053]

$$\sigma(\delta p_T^{\mathrm{jet}}) \propto R$$

$$\delta p_{\mathrm{T}} = p_{\mathrm{T,jet}}^{\mathrm{reco}} - \rho \cdot A_{\mathrm{jet}} - p_{\mathrm{T}}^{\mathrm{part,embed}}$$

We embed different probes into Pb-Pb events and estimate the background response through δp_T

-Small dependence on the probe fragmentation pattern

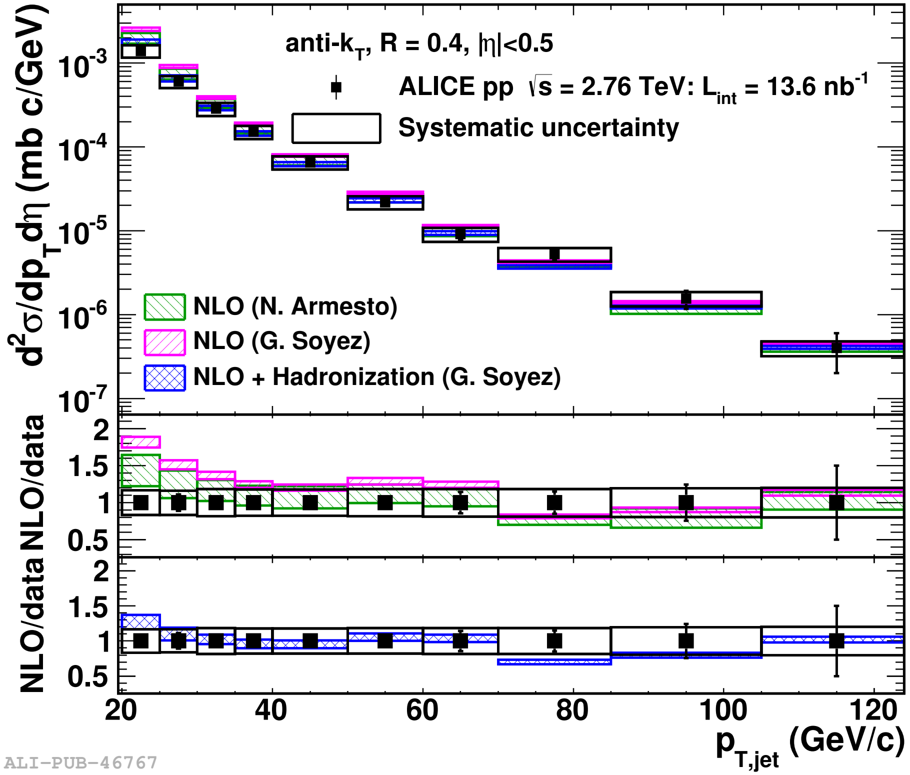
-Small **back reaction** effects in the tails of the response due to jet splitting and jet merging

-Minimum constituent p_T cut-off reduces fluctuations

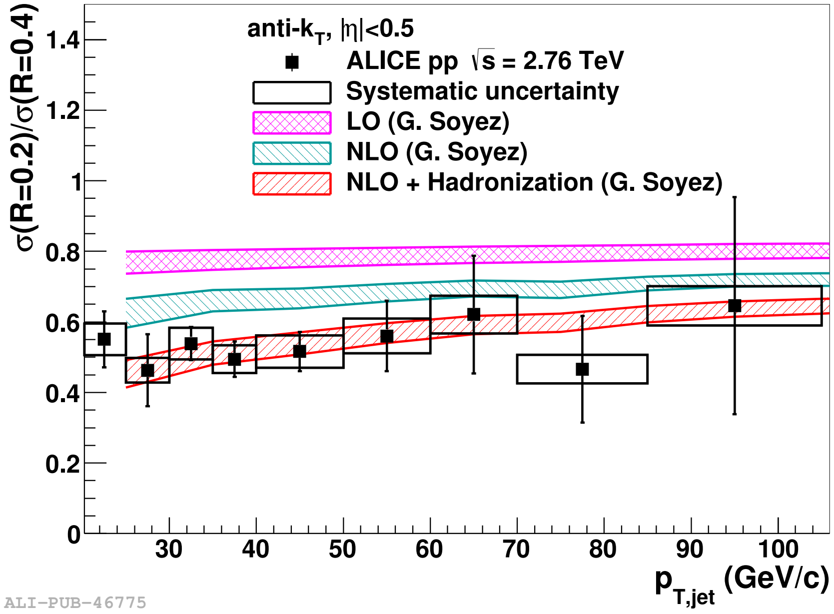
Inclusive yields in pp

Full jets

Inclusive cross section



Ratio of yields for different R



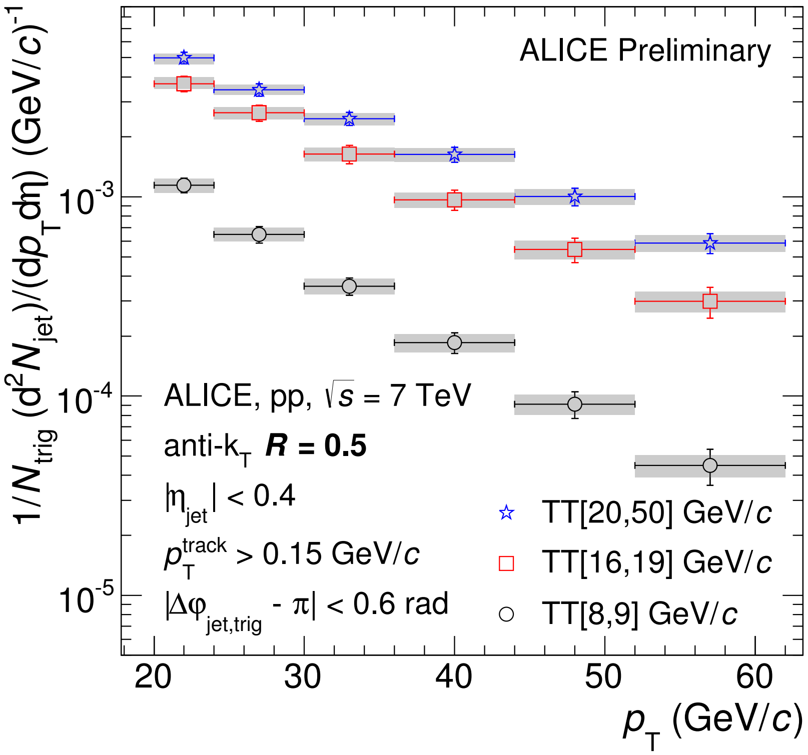
Good agreement with NLO calculations+hadronization corrections

Ratio of yields at different resolution *R* probes the transverse jet energy profile (NLO directly on the ratio → NNLO on the yield)

[ALICE, PLB722 (2013) 262]

Recoil yields in pp

Charged jets



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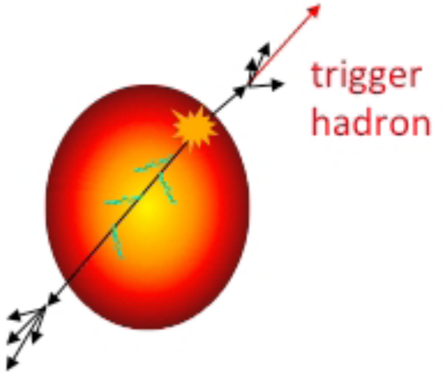
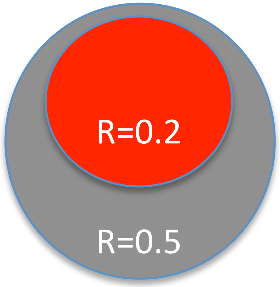


- -Inclusive selection of a high-p_{T} hadron trigger
- -Measure semi-inclusive (per trigger) distribution of jets in the recoil region
- -Dial up the trigger p_{T} → increase the Q^2 of the hard scattering → harden the recoil jet spectrum

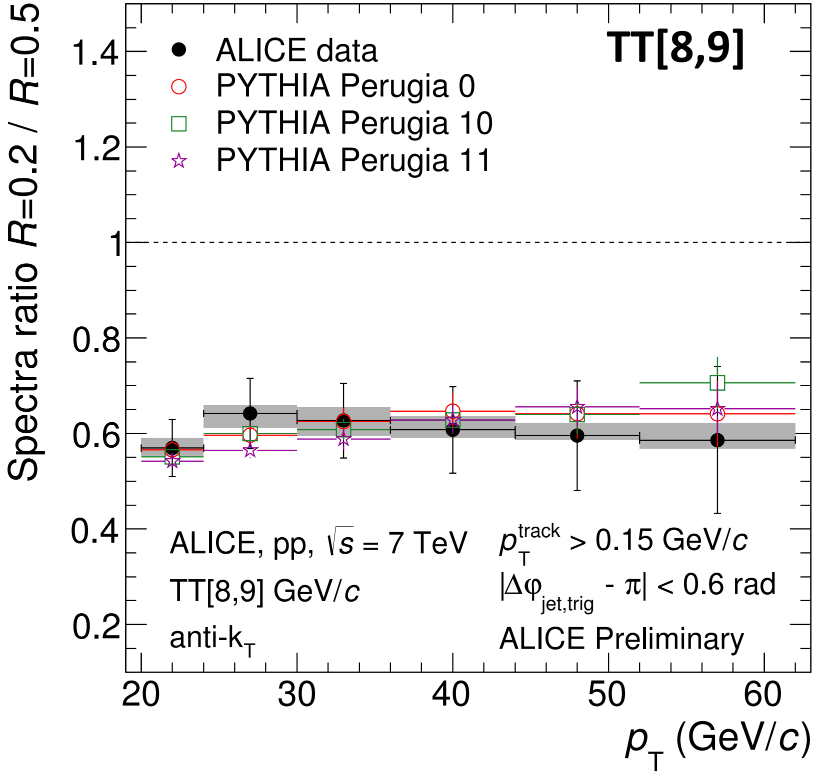
Conceived as a reference for identical Pb-Pb measurements

Recoil yields in pp



Increase of trigger hadron p_T → probe jet collimation

Well reproduced by generators



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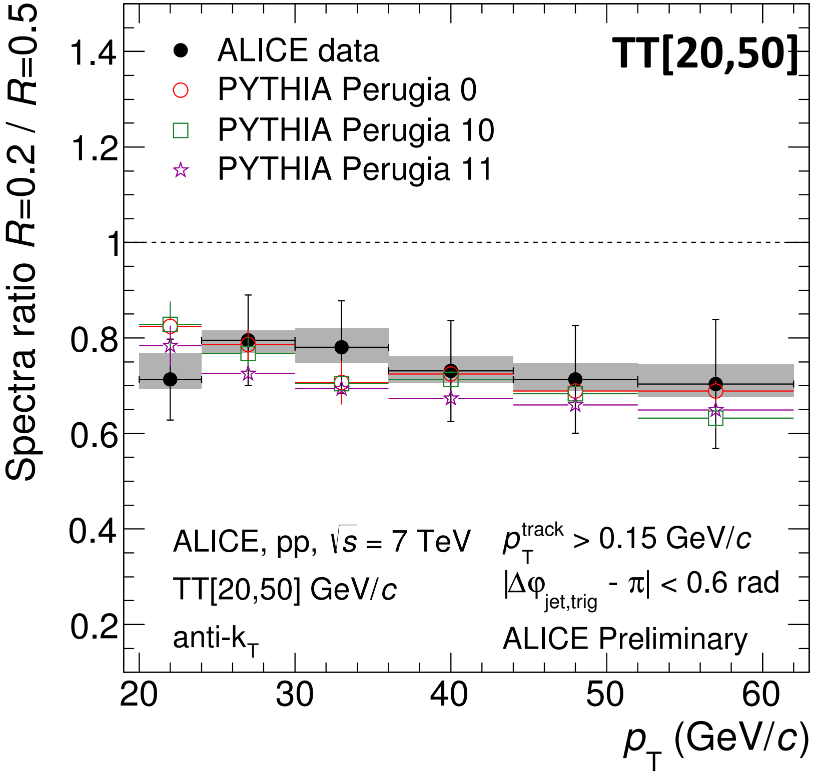

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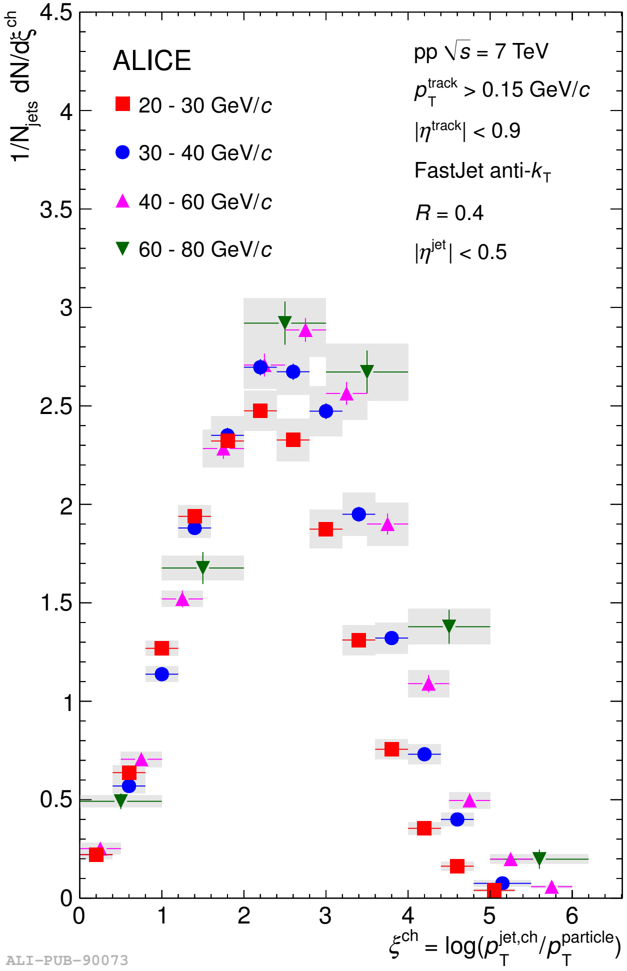
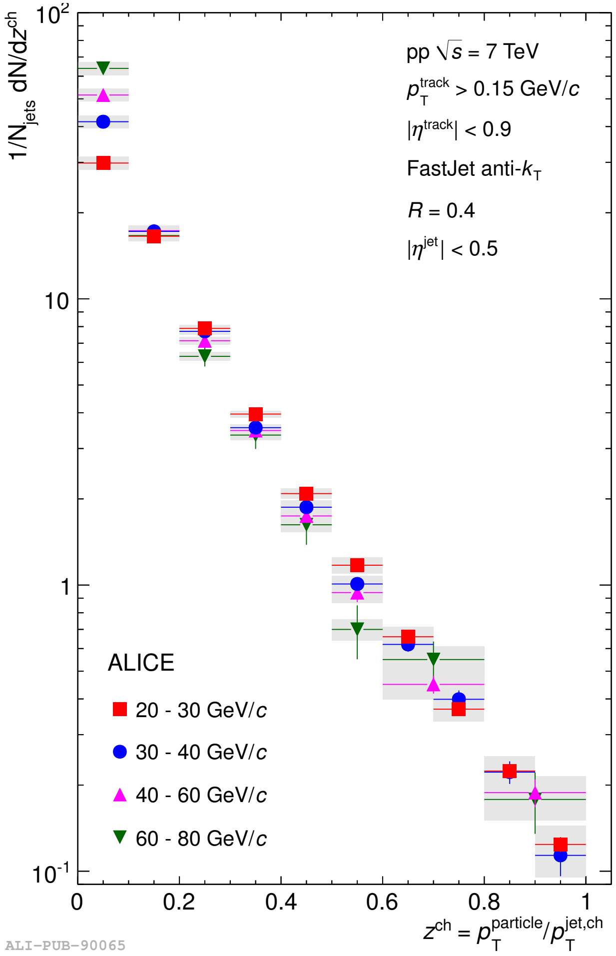
Conceived as a reference for identical Pb-Pb measurements

Charged jets in pp: fragmentation distribution



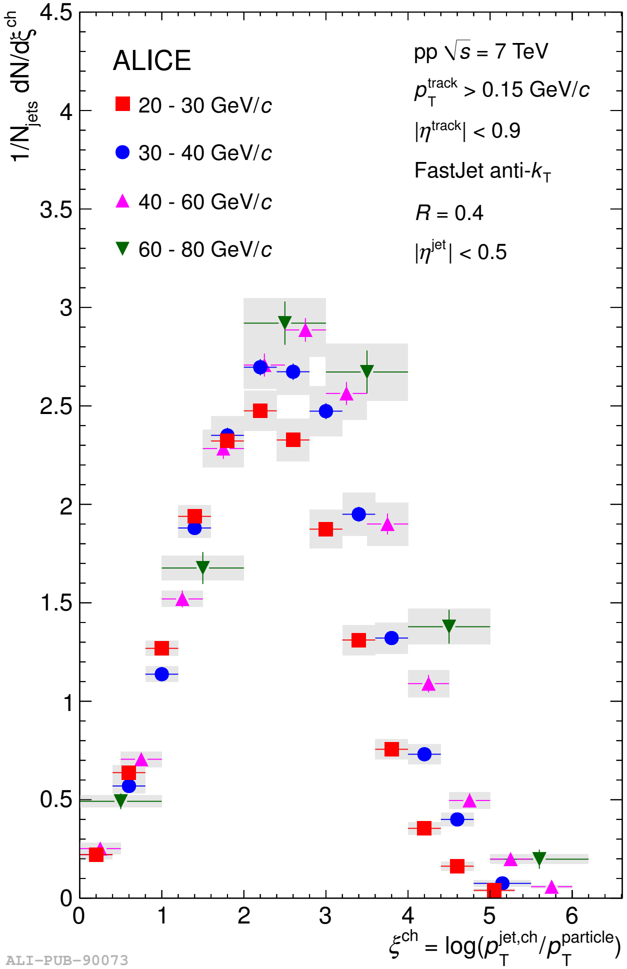


[arXiv:1411.4969]

Hump-backed plateau → suppression of low momentum particles due to color coherence

Approximate scaling at high z

Charged jets in pp: fragmentation distribution



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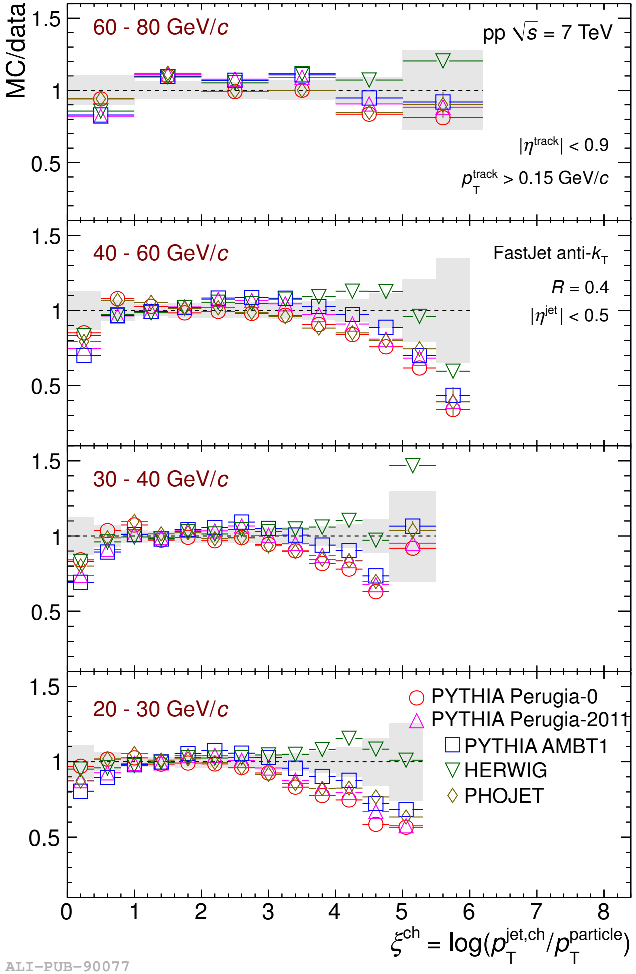


ALI-PUB-90077

[arXiv:1411.4969]

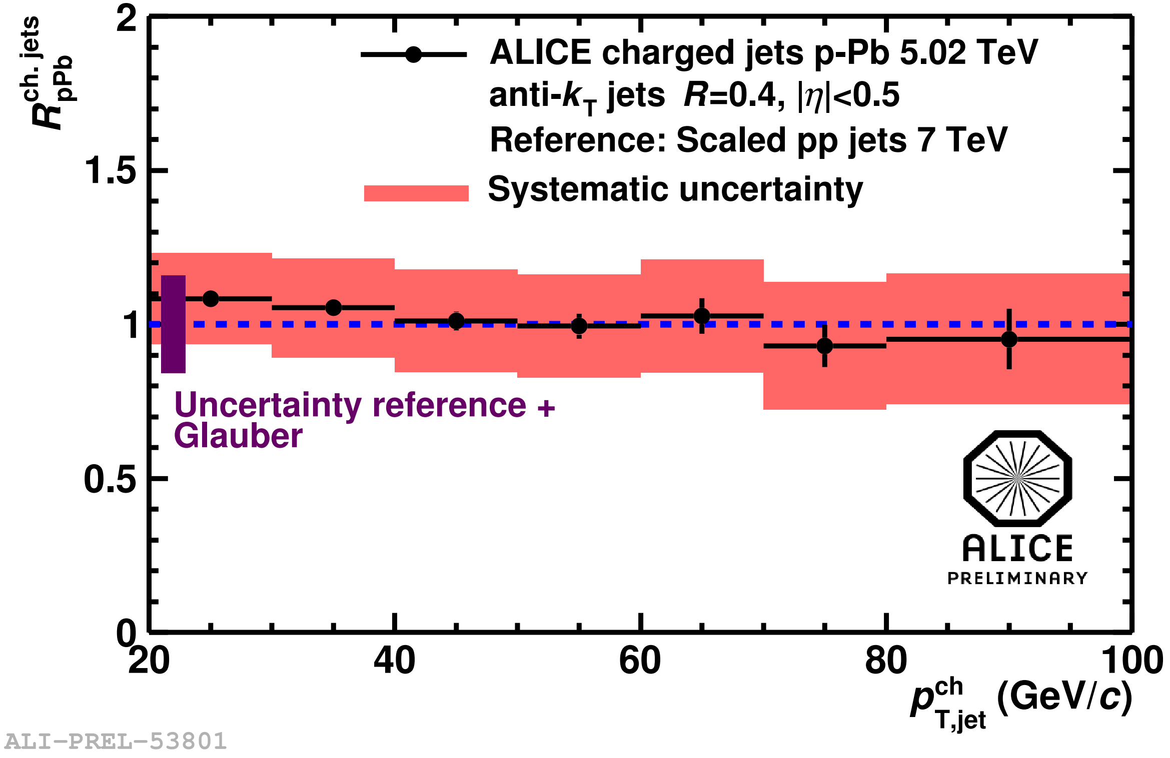
Hump-backed plateau → suppression of low momentum particles due to color coherence

Approximate scaling at high *z*

HERWIG, with exact angular ordering, gives a better description at low p_T

Jet yield suppression in p-Pb?

R_{pPb}: ratio of the yields in p-Pb and pp scaled by the number of binary collisions

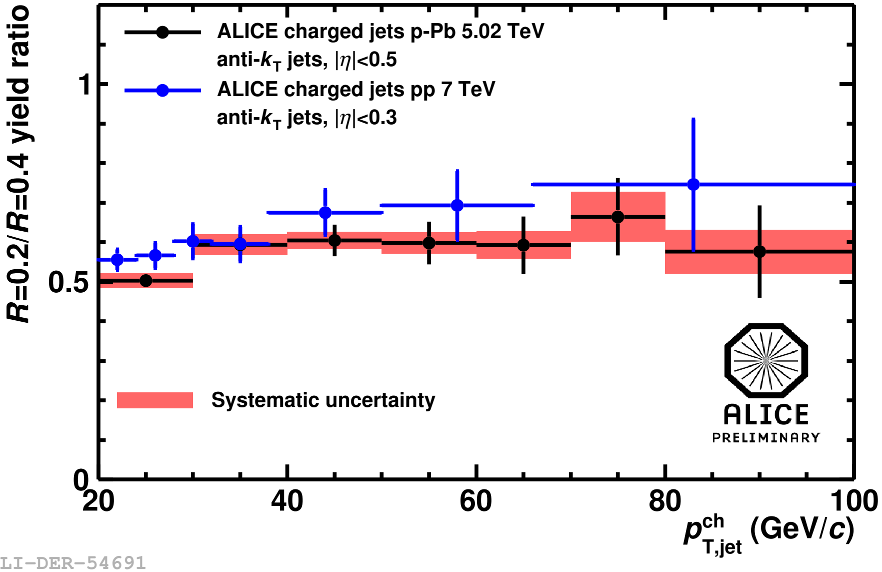


$R_{p\text{-}Pb}$~ 1 in MB events, jet yield compatible with what is expected from a superposition of independent pp collisions → no evidence for nuclear matter effects

Intra-jet broadening in p-Pb?

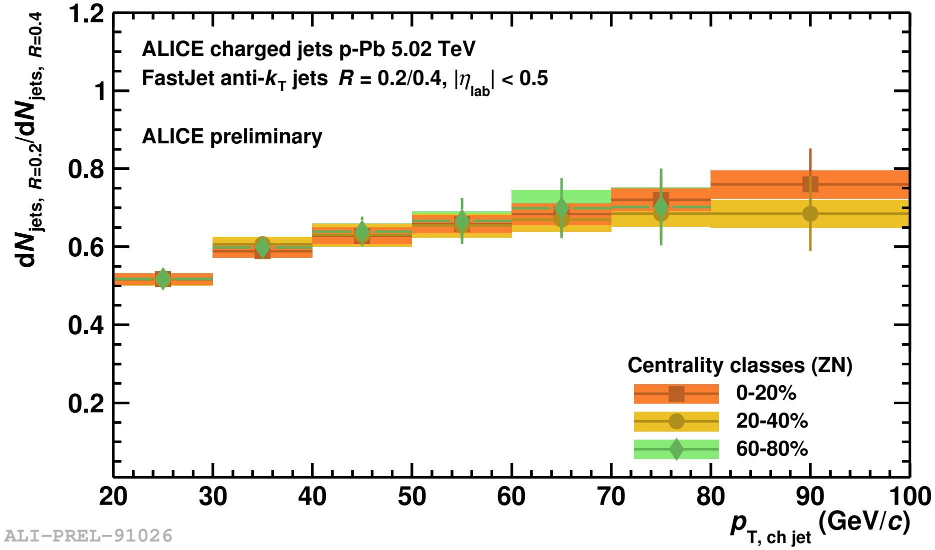
The ratio of yields for different R

MB p-Pb vs pp



ALI-DER-54691

p-Pb various centralities



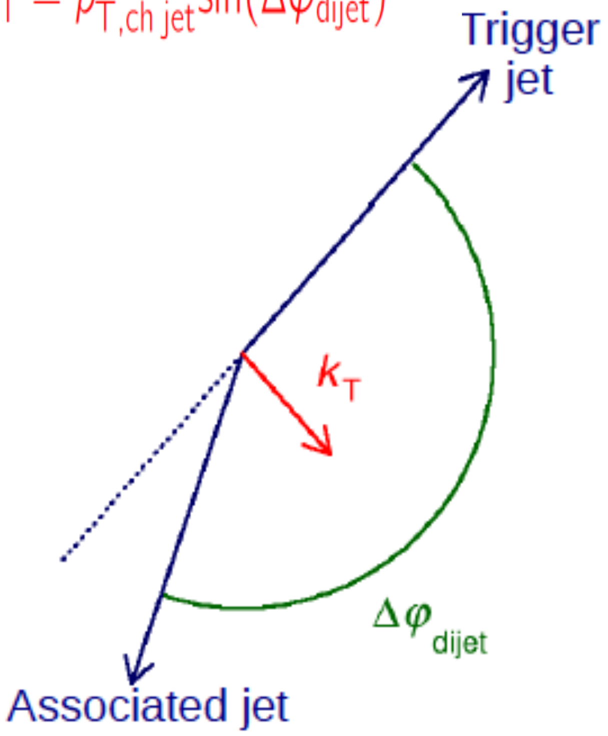
ALI-PREL-91026

No significant intra-jet broadening in p-Pb compared to pp within R=0.4
No evidence for multiplicity dependence

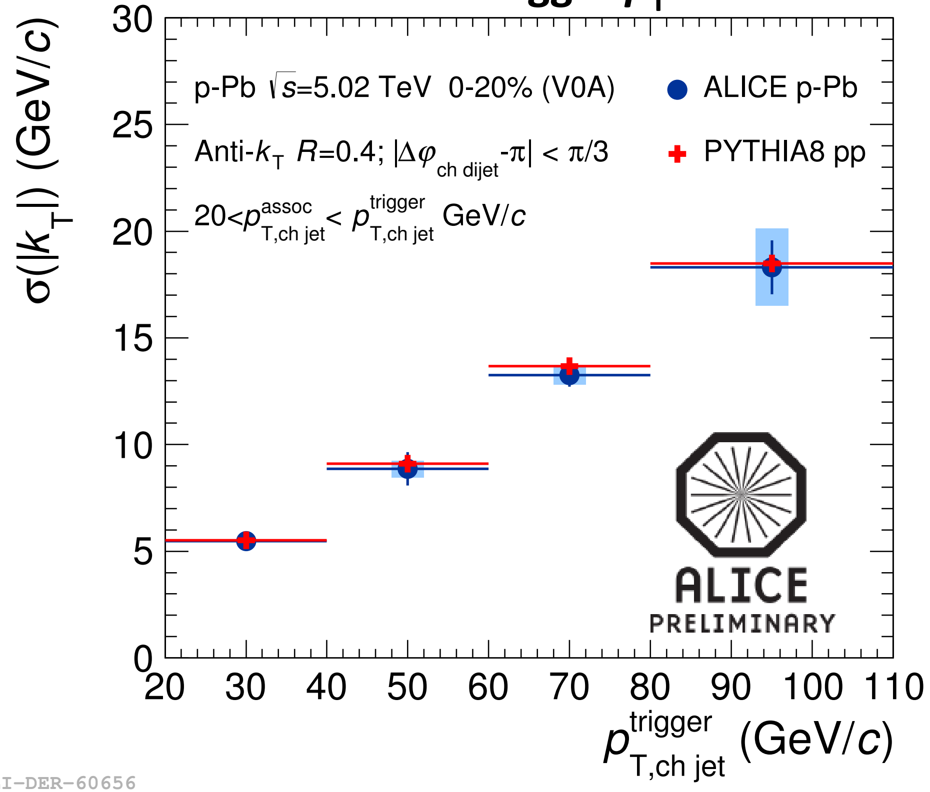
Note different CMS energy in the pp measurement. Same conclusion holds for a Pythia calculation at 5.02 TeV

Inter-jet broadening in p-Pb?

$k_T = p_{T,\mathrm{ch\ jet}}^{\mathrm{trigger}} \sin(\Delta\varphi_{\mathrm{dijet}})$



k_T width (RMS of measured distribution) as a function of trigger p_T

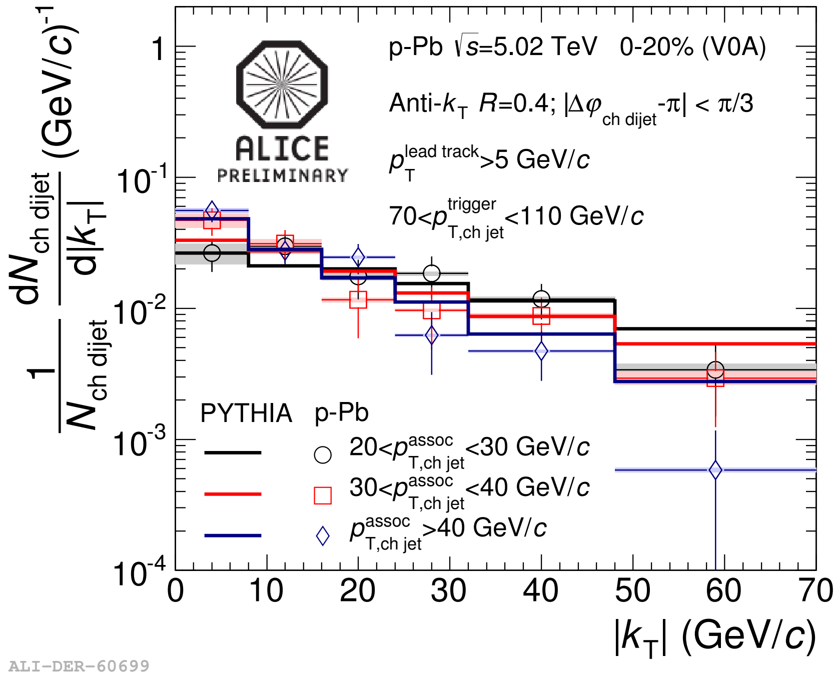


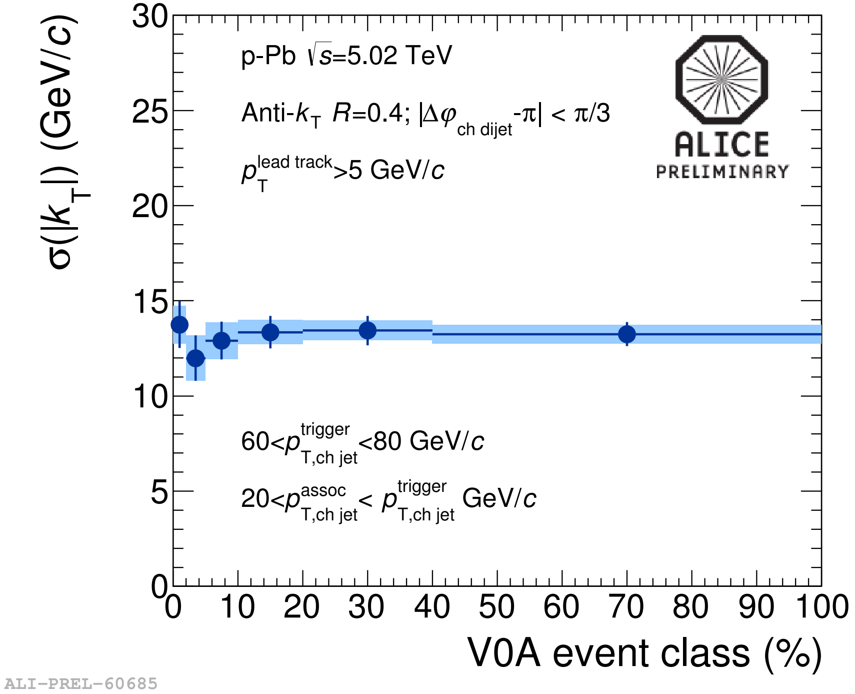
ALI-DER-60656

Sources of acoplanarity in pp: intrinsic k_T, 3-jet events, hard FSR, ISR
Additional sources in p-Pb: interaction of the partonic projectile with the nuclear medium.

No additional effects in p-Pb compared to Pythia

Inter-jet broadening in p-Pb?

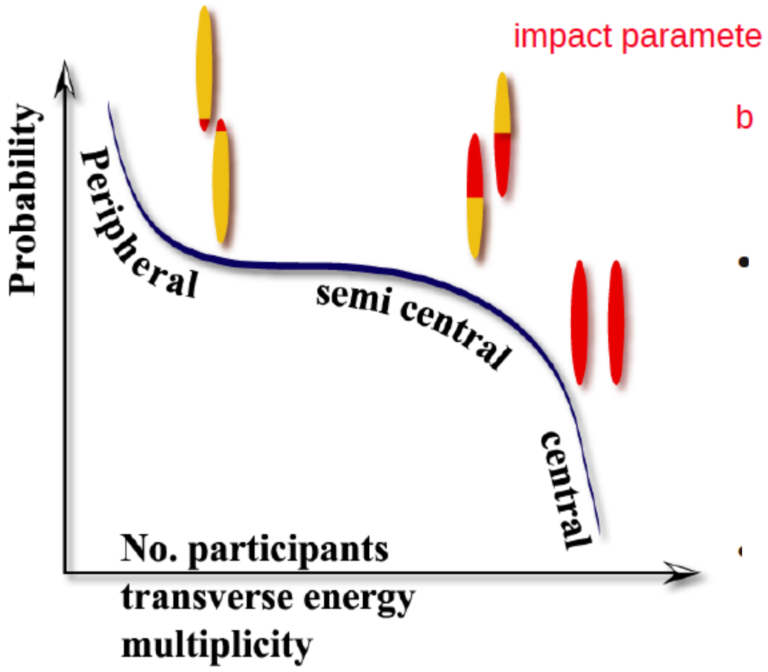




k_T distribution consistent with Pythia in dijet events with large momentum imbalance

No significant change of the k_T width with event multiplicity

Jets in Pb-Pb: some definitions



$$R_{\mathrm{CP}} = \frac{\left.\dfrac{1}{\langle T_{\mathrm{AA}}\rangle}\dfrac{1}{N_{\mathrm{evt}}}\dfrac{\mathrm{d}^2N_{\mathrm{ch\,jet}}}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\eta}\right|_{\mathrm{central}}}{\left.\dfrac{1}{\langle T_{\mathrm{AA}}\rangle}\dfrac{1}{N_{\mathrm{evt}}}\dfrac{\mathrm{d}^2N_{\mathrm{ch\,jet}}}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\eta}\right|_{\mathrm{peripheral}}}$$

Central events (b~0): higher density, larger medium volume

T_{AA} is the overlap function obtained from Glauber model

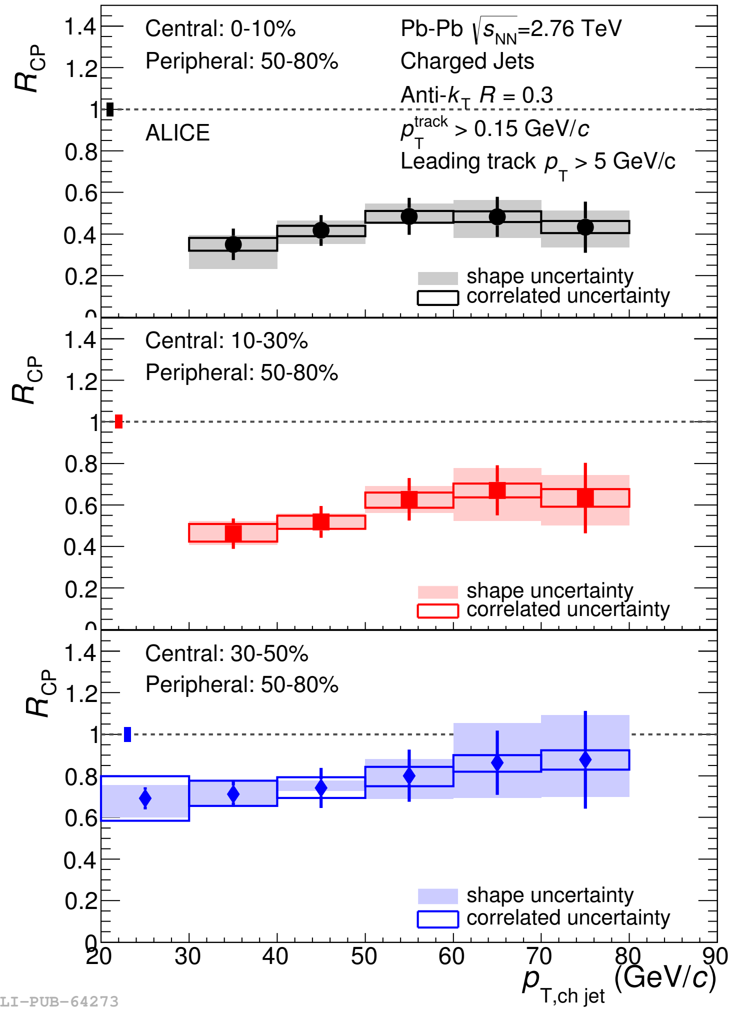
R_{CP} measures the suppression of the jet yield in events with larger medium effects relative to events with smaller medium effects

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}}\rangle}\frac{dN_{AA}/dp_{\mathrm{T}}}{d\sigma_{pp}/dp_{\mathrm{T}}}$$

The Nuclear Modification Factor R_{AA} measures the jet yield in AA collisions relative the case where the AA event were a superposition of independent pp collisions

Jets in Pb-Pb: inclusive yield suppression and intra-jet broadening

Charged jets



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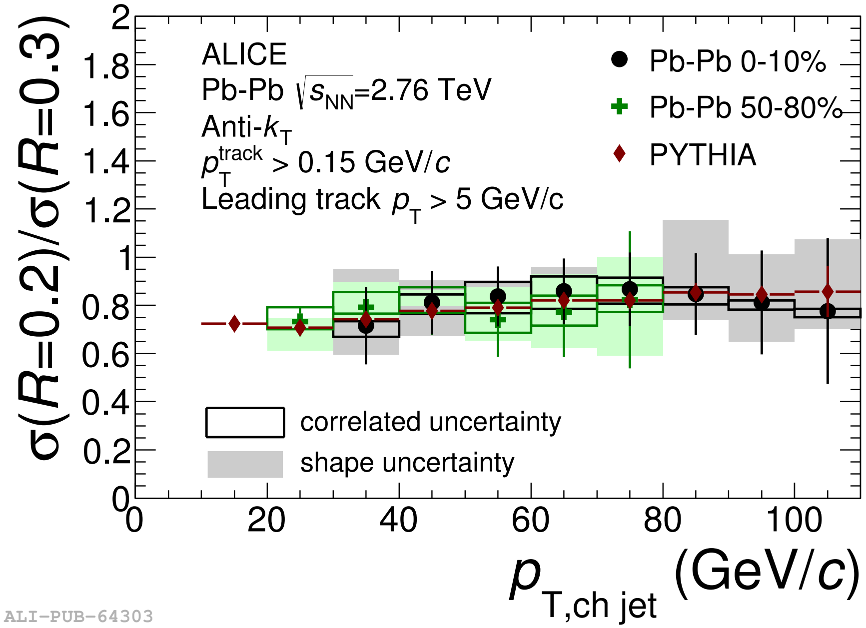

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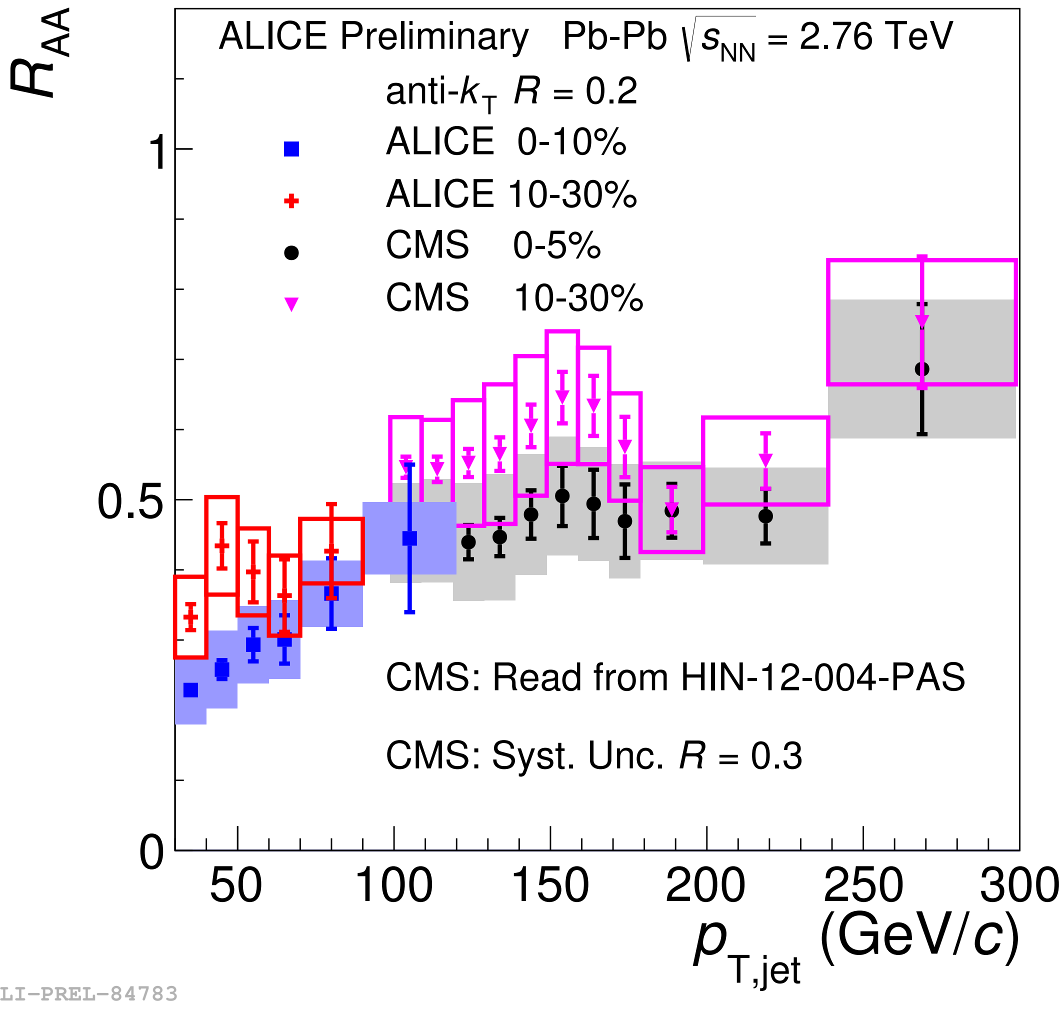
Bias fragmentation (leading track requirement of p_T >5 GeV/c) to suppress combinatorial background

Significant yield suppression & **no intra-jet broadening within R=0.3** in central compared to peripheral

[ALICE,JHEP03(2014)013]

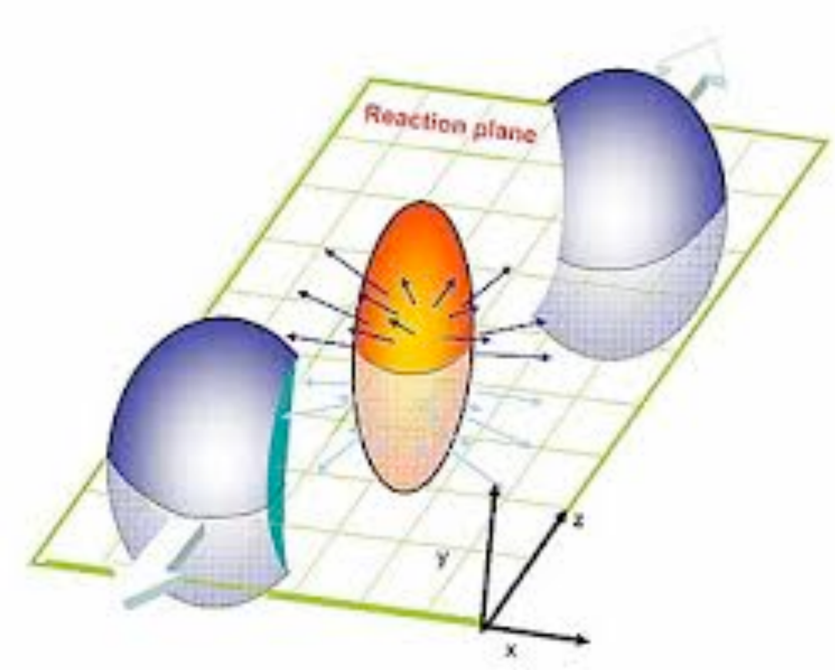
Jets in Pb-Pb: inclusive yield suppression compared to CMS



ALICE complementary measurement at low jet p_T

The medium is opaque for jets up to $p_{T,jet}$~ 300 GeV/c

Jets in Pb-Pb: path length dependence



In a peripheral collision the in-medium path length L "seen" by the projectile parton is shorter in-plane (x-z) than out-of-pane (y-z)

The larger L, the more energy loss (i.e. LPM predicts a L^2 dependence)

Do we see a different jet rate in plane and out of plane?

Quantify the asymmetry via the second coefficient of the Fourier decomposition of the azimuthal distribution of jets relative to reaction plane:

$$\frac{dN}{d(\varphi_{jet} - \Psi_{RP})} \propto 1 + \sum_{n=1}^{\infty} 2v_n^{jet} \cos[n(\varphi_{jet} - \Psi_{RP})]$$

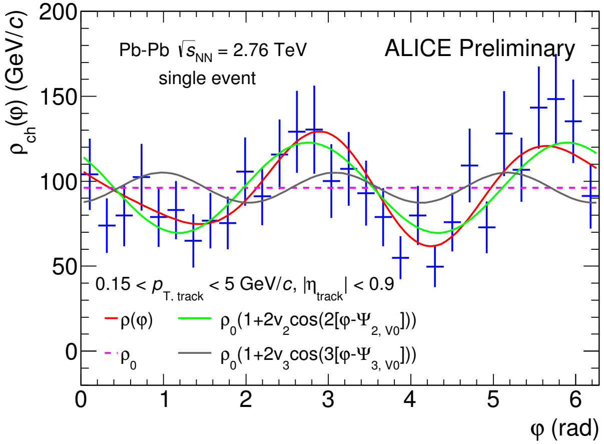
Jets in Pb-Pb: path length dependence

Charged jets

Background density is different in-plane and out-of-plane: local definition of ρ is needed:

$$\rho_{ch}(\varphi) = \rho_0 \left(1 + 2\left\{v_2 \cos[2(\varphi - \Psi_{2,V0})] + v_3 \cos[3(\varphi - \Psi_{3,V0})]\right\}\right)$$

$$p^{ch}_{T,\,jet} = p^{ch}_{T,\,jet,\,raw} - \rho_{local} A \quad \text{with} \quad \rho_{local} = \frac{\langle \rho \rangle}{2R\rho_0} \int_{\varphi-R}^{\varphi+R} \rho(\varphi)\, d\varphi$$



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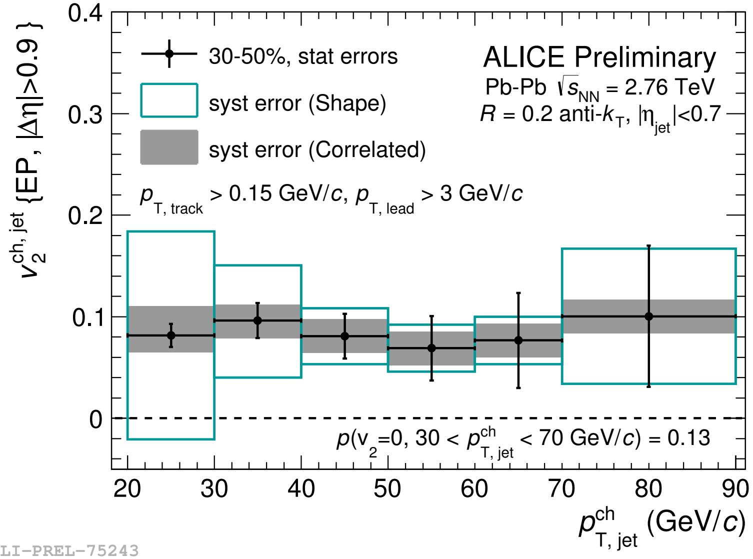
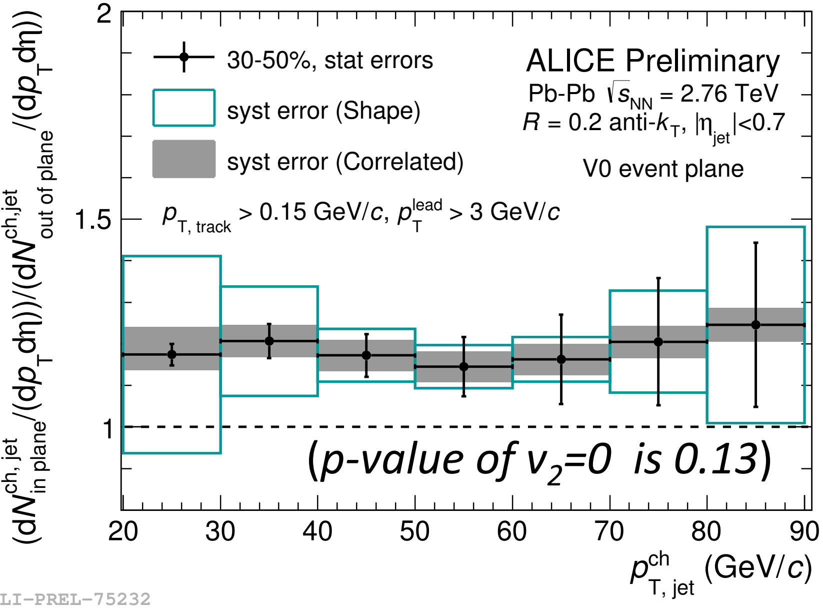


ALI-PREL-75243



(p-value of v_2=0 is 0.13)

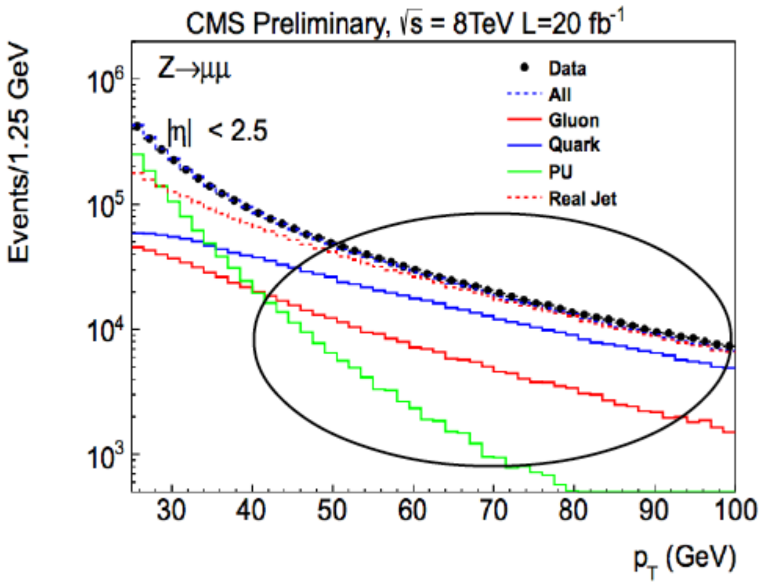
ALI-PREL-75232

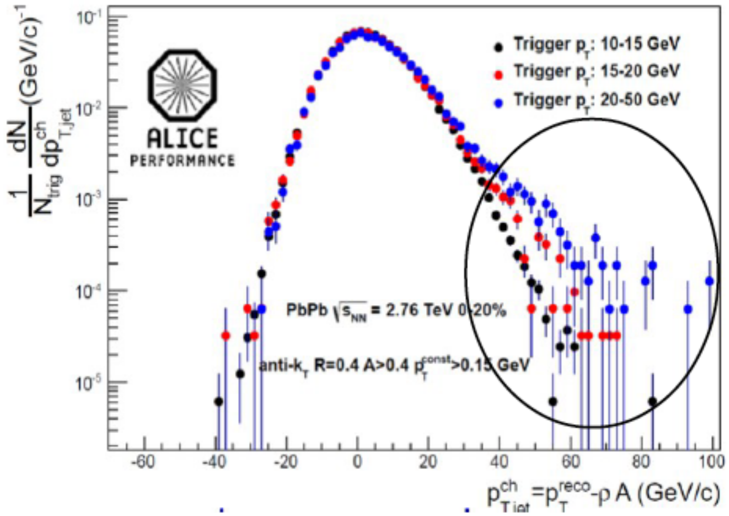
Finite asymmetry: 20-30% effect in the yields, 10% effect in v_2

Pileup Jets or “Fake” Jets

- Pileup jet can be viewed as overlapping low p_T jets
  - **Consider the Jet substructure of such an object?**

$P(\text{overlap}|pT) \approx C\, N^2_{pu}\, a^2_{jet}\, pT^{-6.2}$ Real Jets $\approx pT^{-5}$

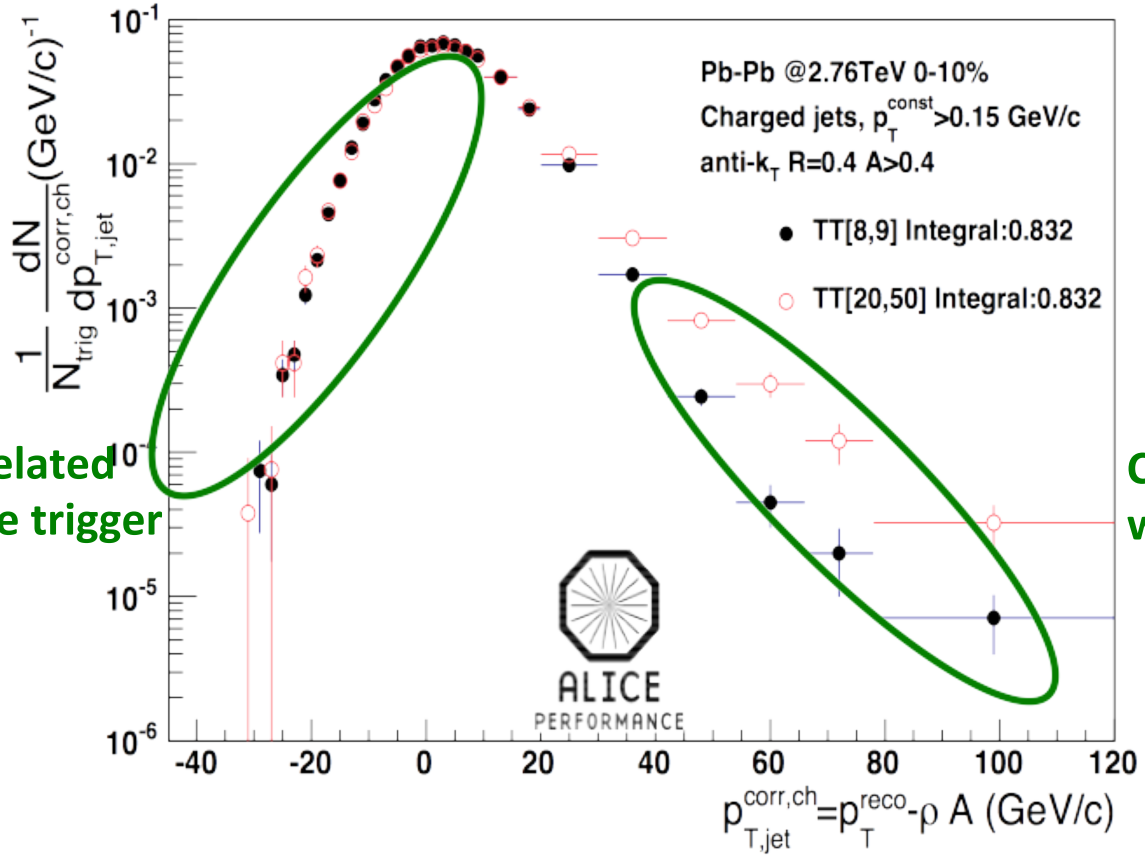




Use dijet topologies (i.e. h-jet) to reduce fake jets with minimal bias on the jet population

Slide from Philip Harris,
3rd heavy ion jet workshop Lisbon July 2014

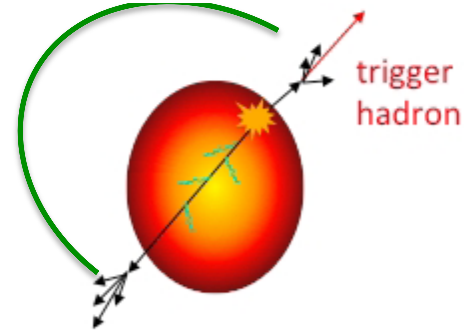
Jets in Pb-Pb: Recoil yields



Uncorrelated with the trigger

Correlated with the trigger

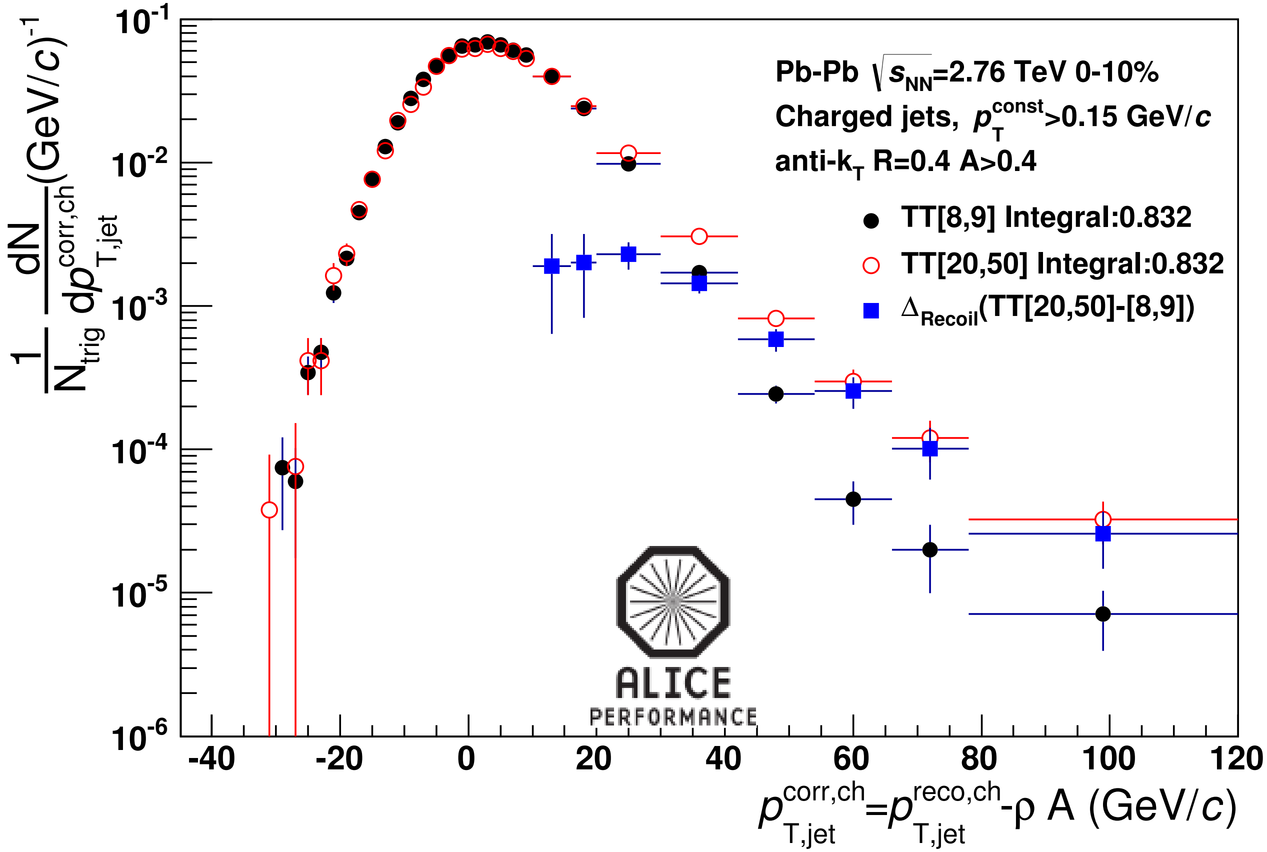
$|\Delta\varphi - \pi| < 0.6$ rad



Combinatorial background uncorrelated with trigger p_T

Opportunity to remove combinatorial background by considering the difference of the jet yields recoiling from two exclusive trigger hadron classes: Δ_{recoil}

Jets in Pb-Pb: Recoil yields



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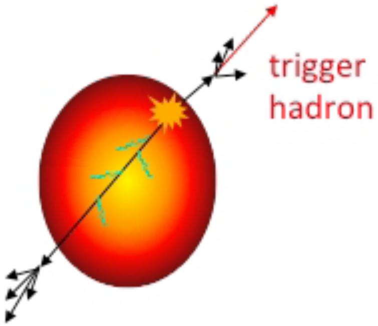
Raw difference observable Δ_{recoil}: yield evolution with trigger p_T

Jets in Pb-Pb: Recoil yields



Semi-inclusive yield of jets recoiling from a high p_T hadron trigger

$$\frac{1}{N^h_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{pp\rightarrow h+X}}\frac{d\sigma^{pp\rightarrow h+jet+X}}{dp_{T,jet}}$$

Measured Calculated e.g. with pQCD@NLO

Using the same technique we study both intra-jet and inter-jet angular broadening:
Remove the combinatorial background by considering the difference
of the recoil yields corresponding to two exclusive (trigger) TT windows, TT_{signal} and $TT_{reference}$

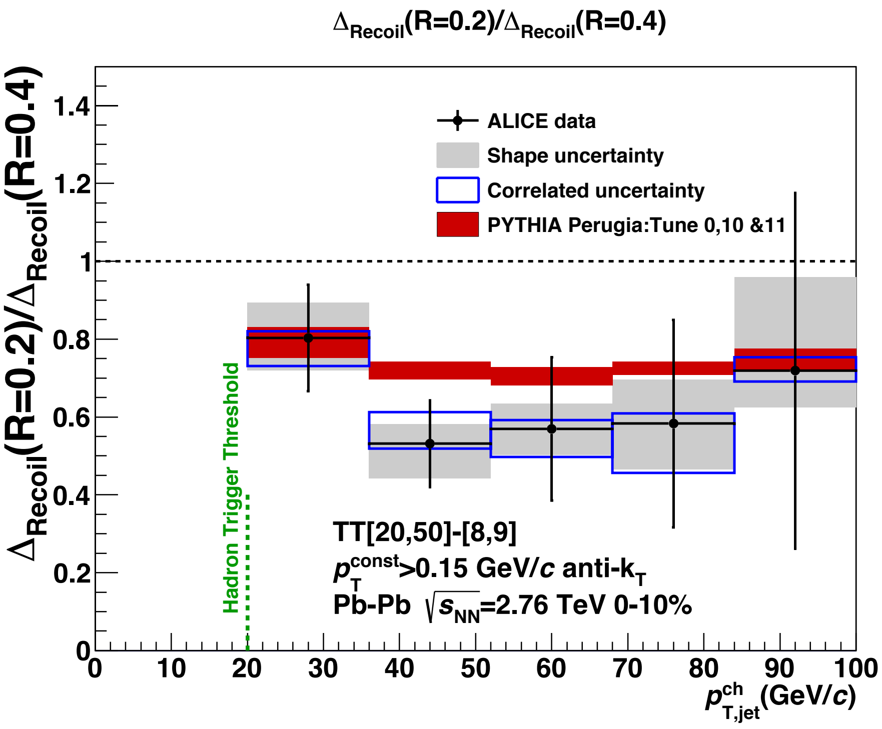
$$\Delta_{recoil}(p_T) = \left(\frac{1}{N_{trig}}\frac{dN}{dp_T}\right)_{signal} - f \times \left(\frac{1}{N_{trig}}\frac{dN}{dp_T}\right)_{reference}$$

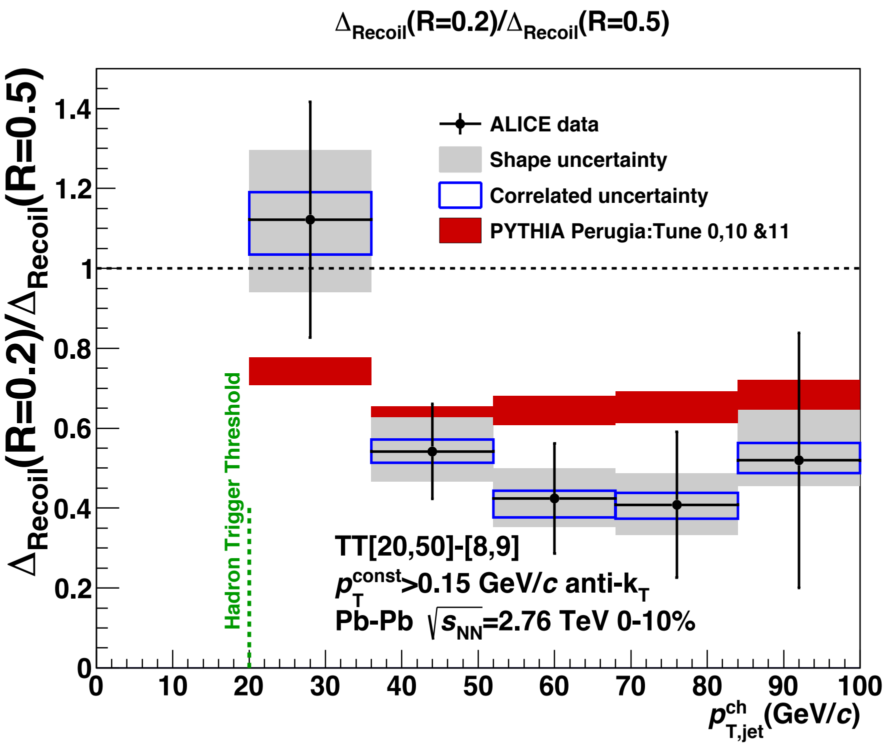
$$\Delta_{recoil}(\Delta\varphi) = \int_{pT1}^{pT2} dp_T \left(\frac{1}{N_{trig}}\frac{dN}{d\Delta\varphi dp_T}\right)_{signal} - f \times \left(\frac{1}{N_{trig}}\frac{dN}{d\Delta\varphi dp_T}\right)_{reference}$$

(f ~ 1)

- Result is distribution of the population of collinear-safe jets with low IR cutoff

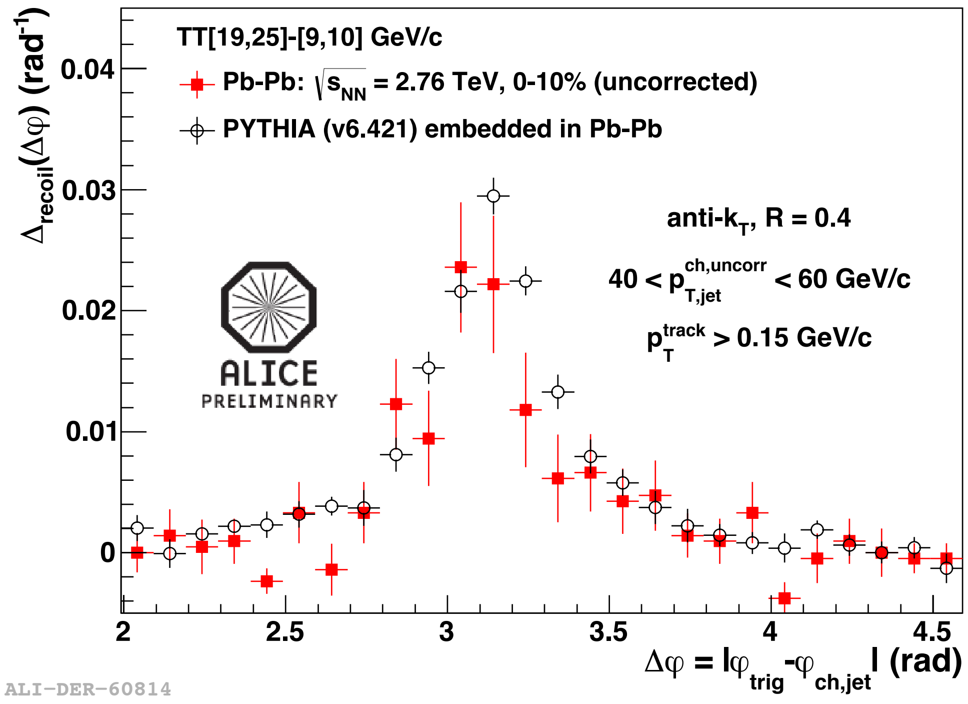
Intra-jet broadening in Pb-Pb

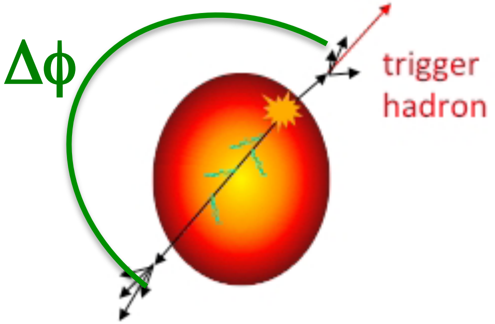




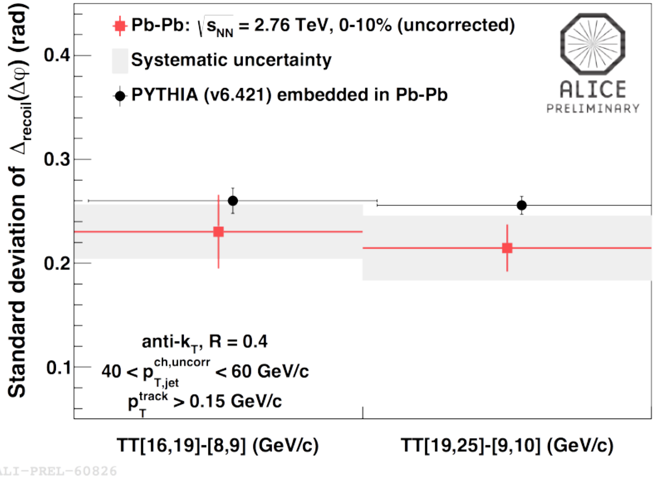
No significant evidence for broadening within the jet cone (R < 0.5) compared to Pythia

Inter-jet broadening in Pb-Pb





Recoil width in Δϕ



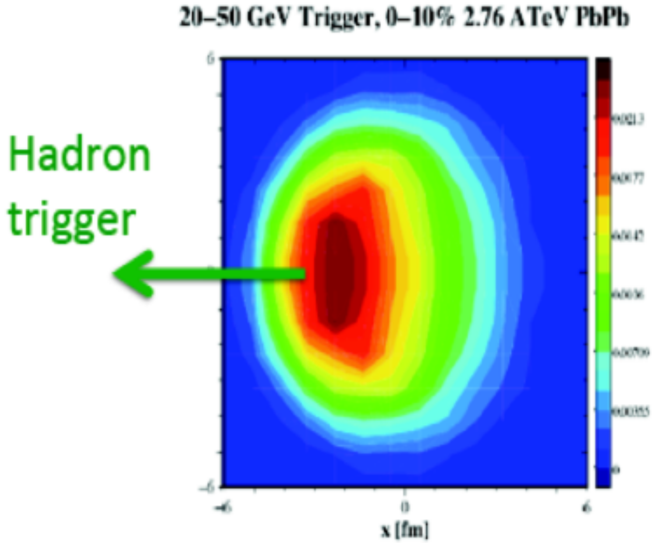
PYTHIA is folded with the detector effects and background fluctuations

PYTHIA : σ_{2Gaus}=0.26±0.03 rad → **Statistically compatible**

PbPb data: σ_{2Gaus}=0.21±0.09 rad

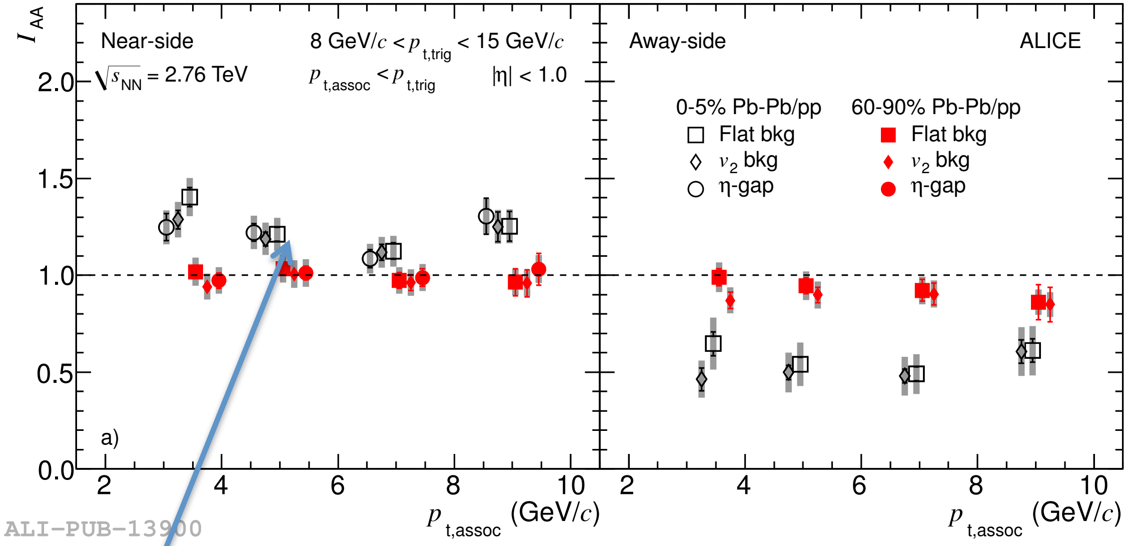
[σ_{2Gaus} is the standard deviation of the full distribution from the fit]

Considerations on h-jet coincidence measurements in Pb-Pb



T.Renk, private com.

1. The hadron trigger imposes a strong surface bias and maximal in-medium path length



[*ALICE,PRL108 092301 (2012)*]

2. Near side energy loss of the trigger

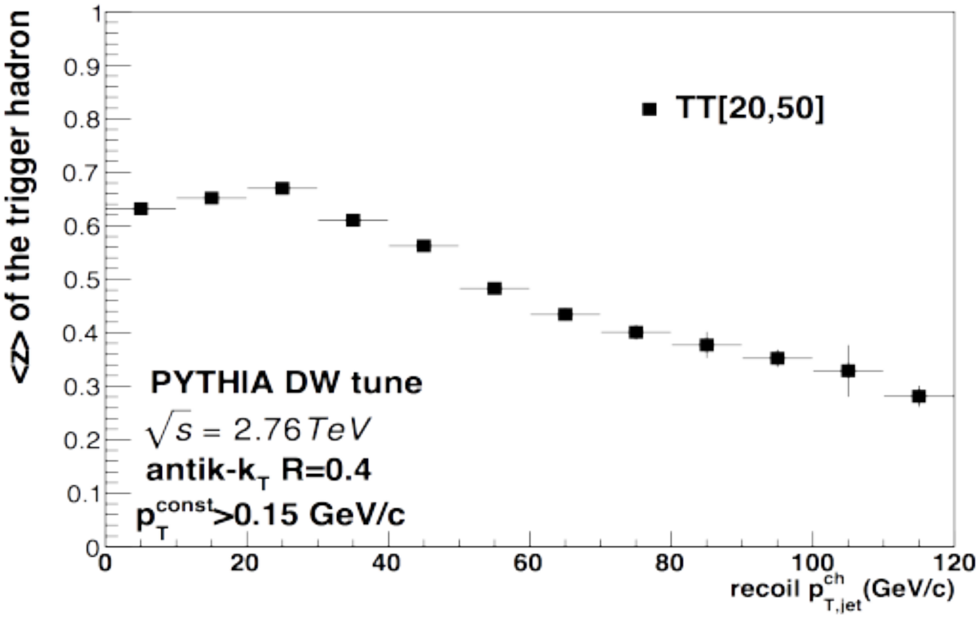
→ the distribution of Q^2 can be different in medium and in vacuum

ALICE single particle I_{AA}>1 also suggests higher Q^2 in medium

extend di-hadron correlations to high p_T

Considerations on h-jet coincidence measurements in Pb-Pb

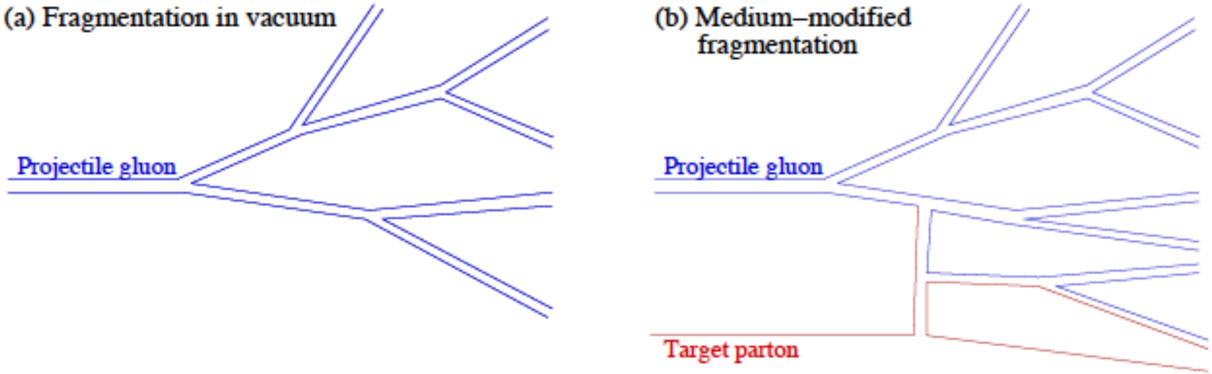
3. Recoil jet spectrum is harder than inclusive: same energy shift due to quenching results in less suppression of the recoil than of the inclusive yields



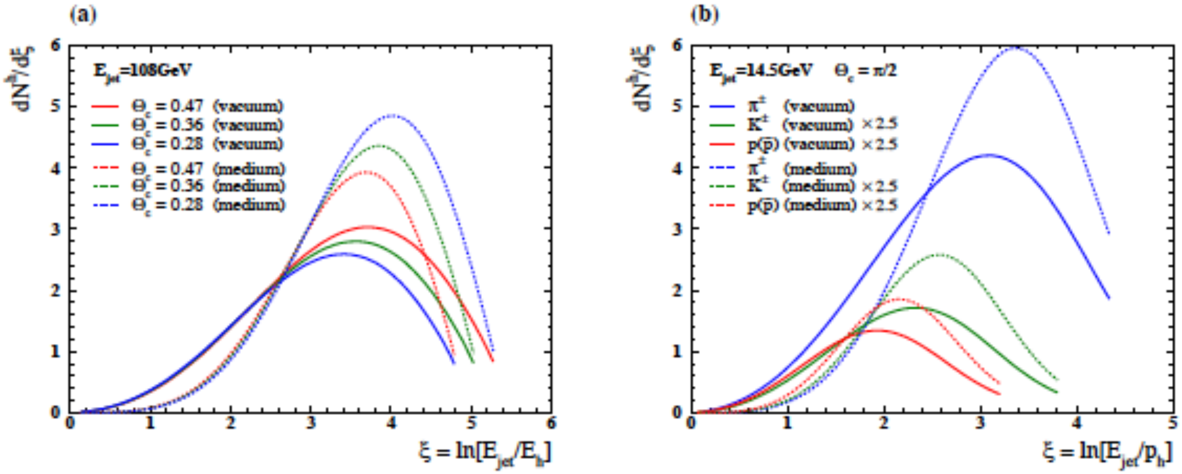
4. For a fixed TT hadron class, increasing recoil jet p_T probes decreasing hadron trigger *z* fraction

Different surface bias for different range in recoil jet p_T?

Jet hadrochemistry



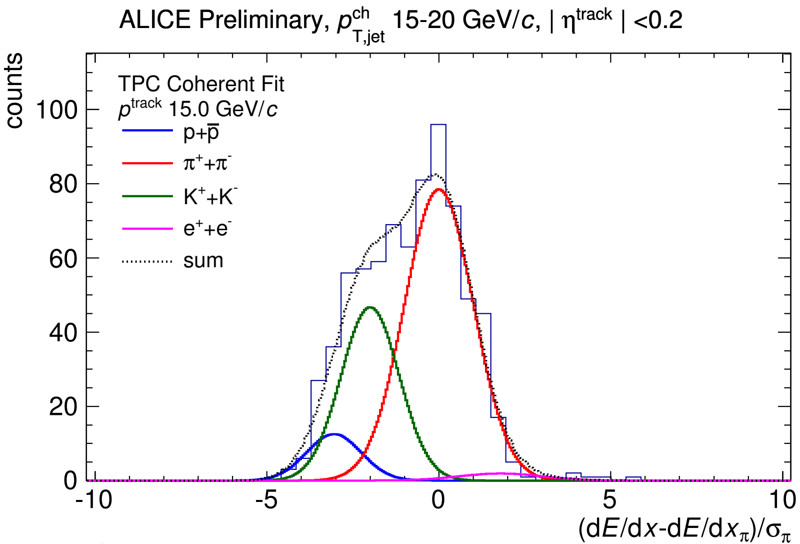
In-medium interactions are expected to change the color flow leading to differences in the hadron composition



[Sapeta,Wiedemann, Eur.Phys.J.C55:293-302,2008]

Hadron composition of charged jets in pp

TPC dE/dx at track p_T=15 GeV



ALI-PREL-70175

TPC coherent Fit: **fit of 2D distribution of dE/dx versus particle momentum.**

Raw differential particle yields

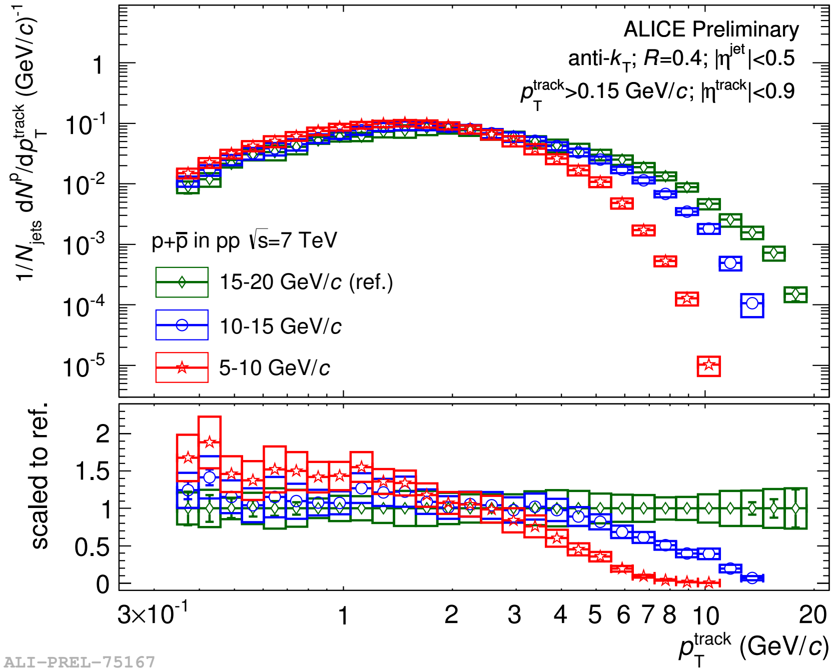
0.15<p_T<20 GeV/c, ~10% accuracy

Baseline techniques

for PID in jets in Pb-Pb collisions

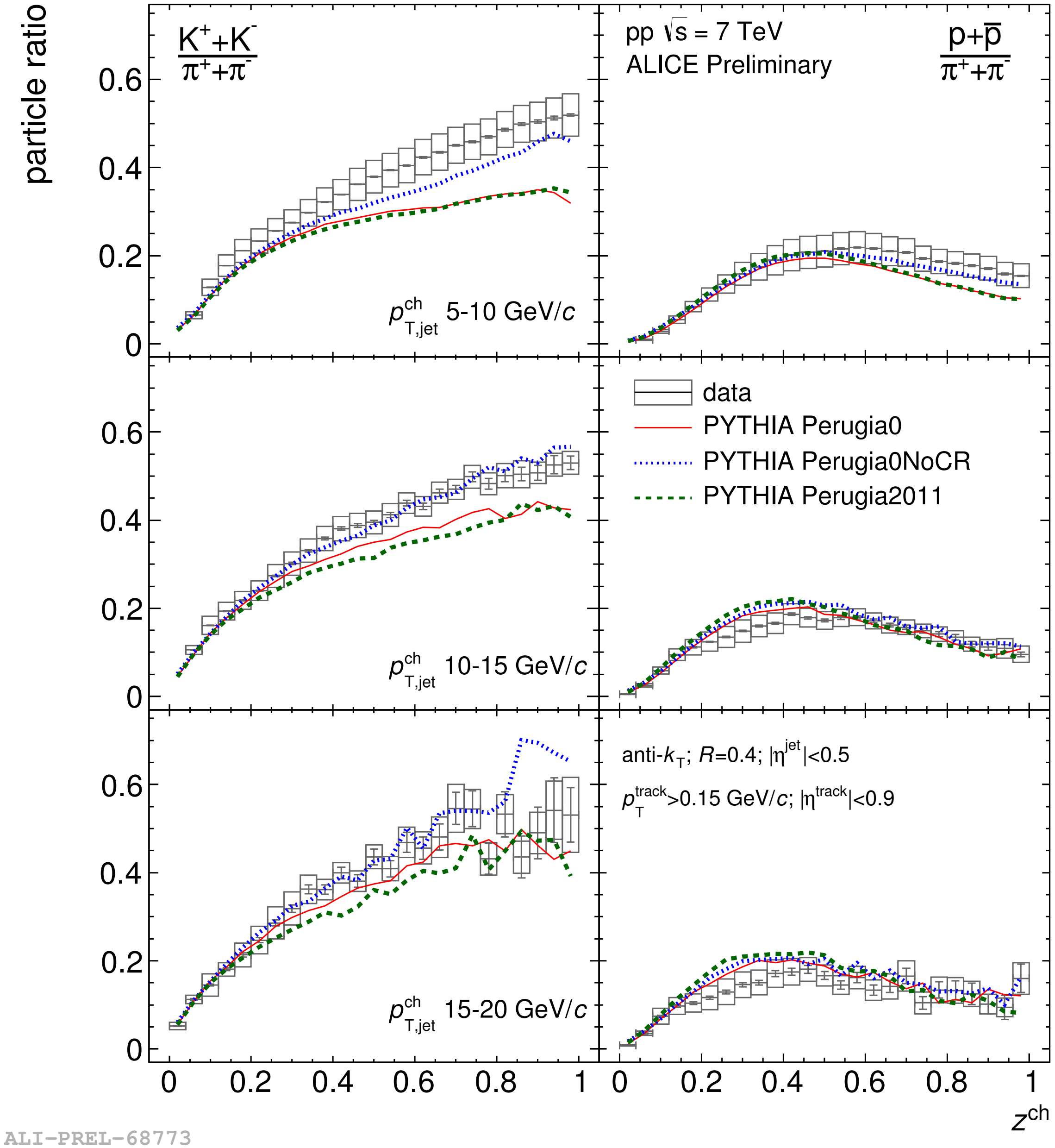
First measurement of particle type dependent jet fragmentation at LHC

Proton yields inside jets



ALI-PREL-75167

Hadron composition of charged jets in pp



ALI-PREL-68773

First measurement of particle type dependent jet fragmentation at LHC

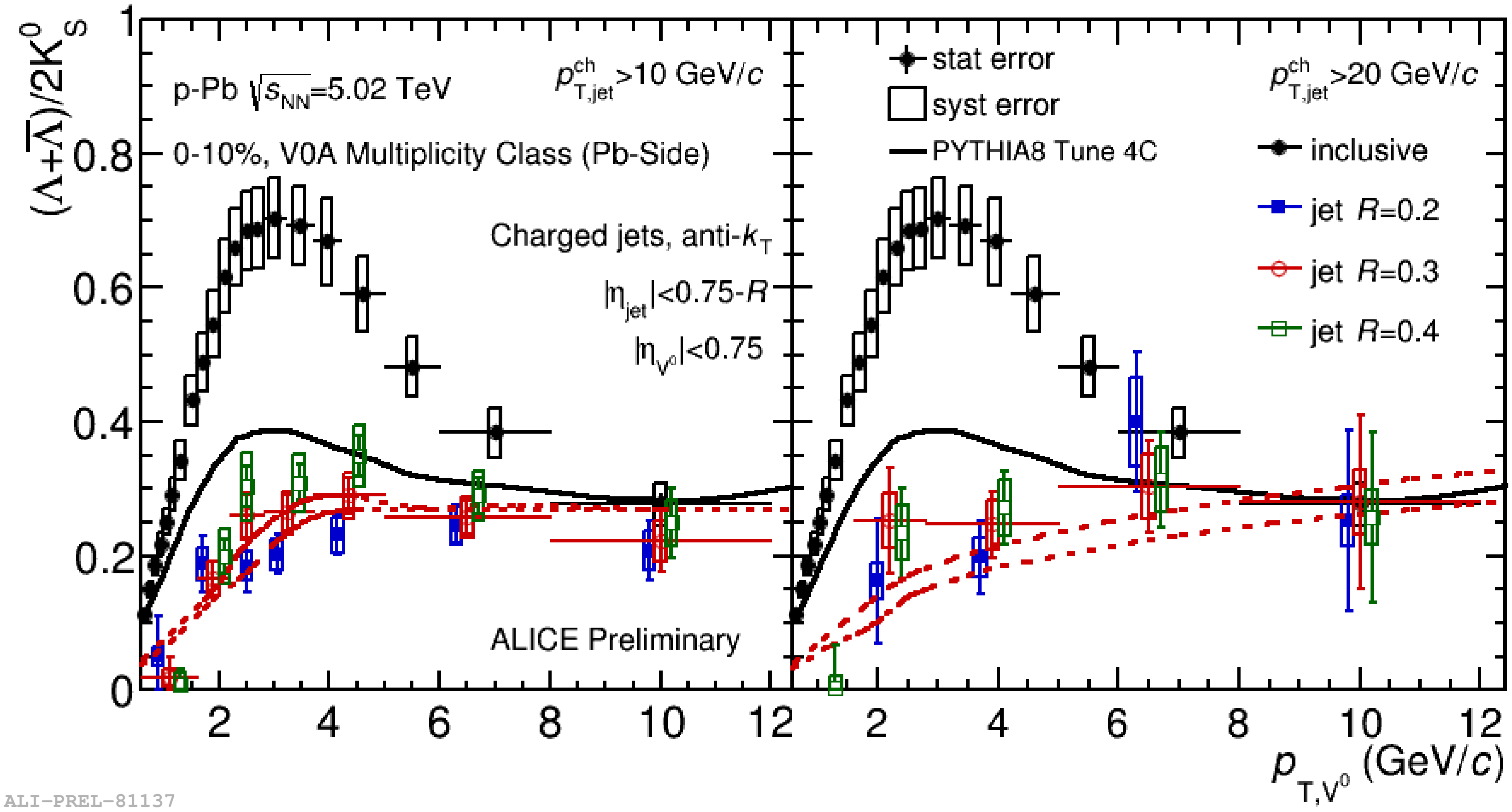
Trends described by PYTHIA

-strangeness rises with z

-leading baryon suppression

TPC coherent fit,
baseline techniques
for PID in jets in PbPb collisions

Hadron composition of charged jets in p-Pb



No baryon enhancement observed in jets, in contrast to inclusive measurements

Ratio of Λ/K^0_S consistent with PYTHIA pp ratio

Inclusive and jet-like consistent at high p_T

Disfavours hard-soft recombination models

Prospects for jet measurements in ALICE

-Precision measurements of intra-jet broadening or jet sub-structure

*Plethora of jet shapes that probe different aspects of the intra-jet distributions: jet mass, angularities, pTD, subjets etc

*New jet shape subtraction techniques available and under test for Pb-Pb

*Can jet shapes in Pb-Pb be used to tag quark/gluon jets? Are color factors driving the differences as in vacuum?

-h-jet coincidence measurements,

*focus on the tails of the angular correlation (look for additional jet yield at large angle, sensitive to differences between strongly and weakly coupled medium)

*study jet substructure

-Subjet correlations

-Observables to characterize radiation at large angles

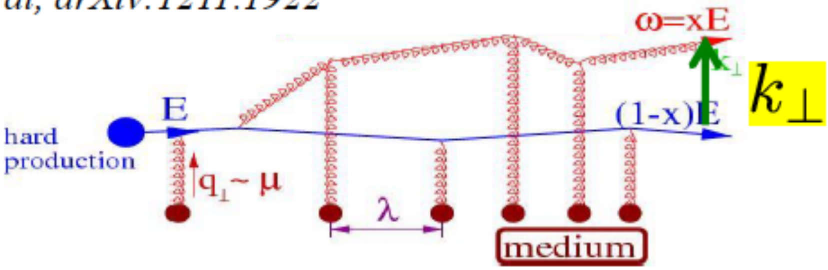
-Particle identification in jets in Pb-Pb, hadrochemistry

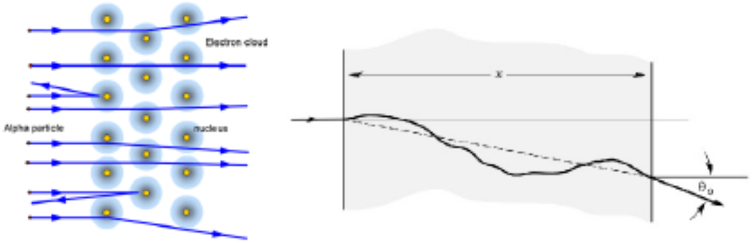
- extras

Large-angle scattering off the QGP

d'Eramo et al, arXiv:1211.1922

Discrete scattering centers or effectively continuous medium?



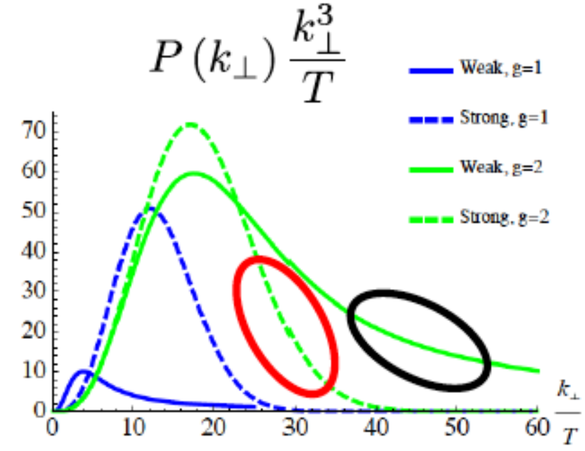


Look at the rate of large-angle deflections (DIS-like scattering off the QGP)

- What are the quasi-particles?

Weak coupling: pQCD: finite temperature plays the role of mass to generate large angle scattering

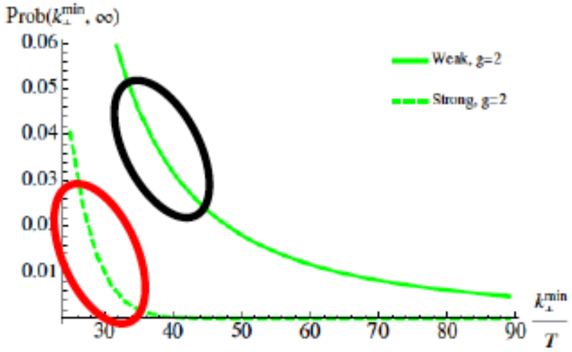
Strong coupling: AdS/CFT



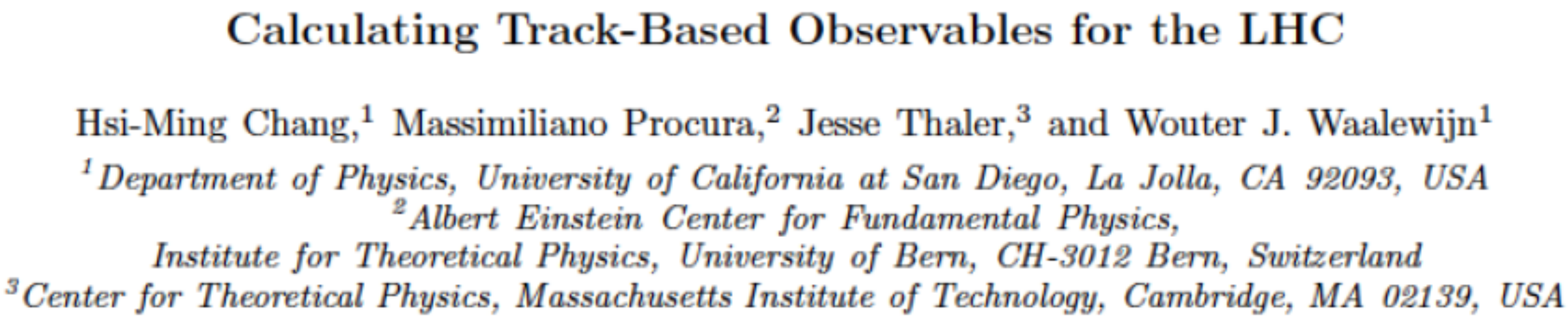
Strong coupling: Gaussian distribution

Weak coupling: hard tail $\sim \frac{1}{k_\perp^4}$

$\text{Prob}\left(k_\perp > k_\perp^{min}\right)$



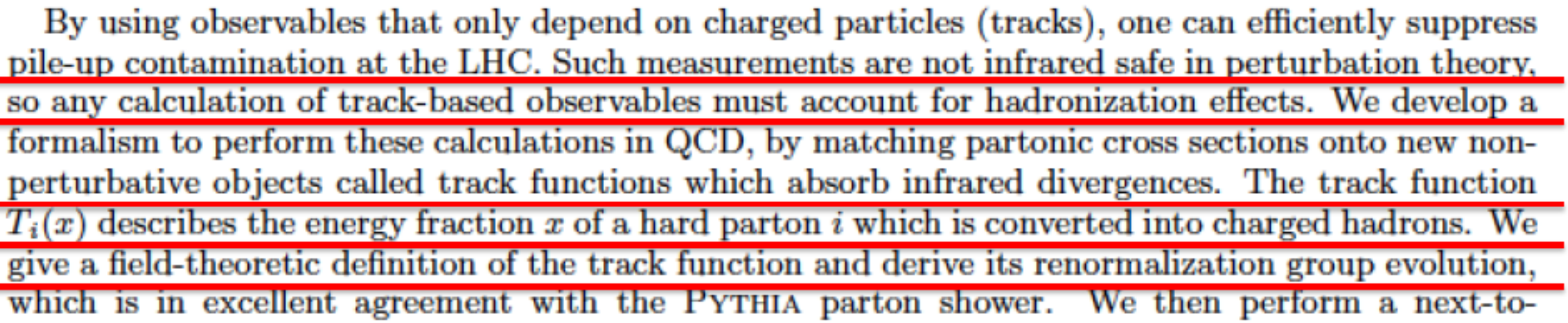
Slide from Peter Jacobs



Calculating Track-Based Observables for the LHC

Hsi-Ming Chang,[1] Massimiliano Procura,[2] Jesse Thaler,[3] and Wouter J. Waalewijn[1]

[1]Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA
[2]Albert Einstein Center for Fundamental Physics,
Institute for Theoretical Physics, University of Bern, CH-3012 Bern, Switzerland
[3]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

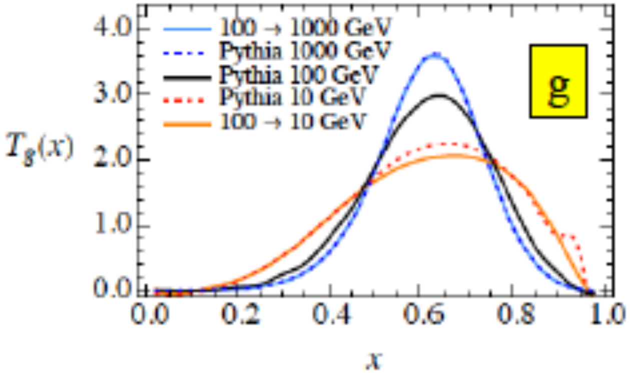


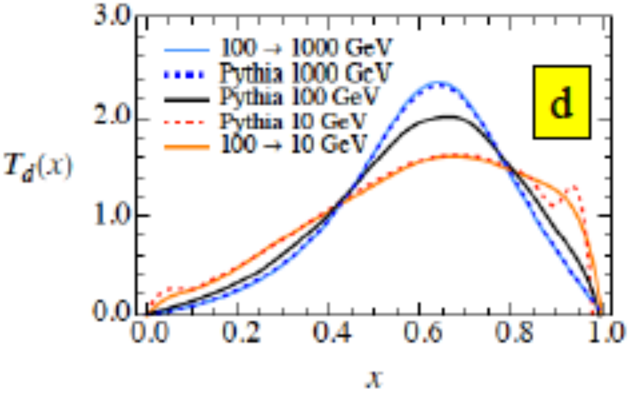
By using observables that only depend on charged particles (tracks), one can efficiently suppress pile-up contamination at the LHC. Such measurements are not infrared safe in perturbation theory, so any calculation of track-based observables must account for hadronization effects. We develop a formalism to perform these calculations in QCD, by matching partonic cross sections onto new non-perturbative objects called track functions which absorb infrared divergences. The track function $T_i(x)$ describes the energy fraction x of a hard parton i which is converted into charged hadrons. We give a field-theoretic definition of the track function and derive its renormalization group evolution, which is in excellent agreement with the PYTHIA parton shower. We then perform a next-to-

Evolution of Track Functions

Track functions have DGLAP-like evolution

- Start with Track functions at μ=100 GeV
- Evolve up to μ=1000 GeV and down to μ=10 GeV
- Compare to PYTHIA jets at 10 and 1000 GeV





Track jets

- as legitimate perturbatively as calo and particle-flow jets
  - ➔not better or worse, just different
- Experimental advantages which we know well, poorer Jet energy resolution
  - ➔different systematics

Track jets should remain in our "experimental arsenal": very interesting to compare Track and Calo jets for the same jet quenching observables