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The physics program of the ALICE experiment at the LHC

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Fifth Conference on
"Perspectives in Hadron Physics"

Trieste, 22-26 May 2006

Contents

- Nucleus-nucleus collisions (and p-p) at the LHC
- The ALICE experiment
- Highlights on some physics topics *
  - Soft physics
  - Heavy Flavours and quarkonia
  - Jets
- Conclusions

* Results of studies published on Physics Performance Report Vol.II, CERN/LHCC 2005-030

Photon physics covered by Y.Kharlov's talk: "Prompt photon physics in the ALICE experiment"

Nucleus-nucleus (and pp) collisions at the LHC

The beams at the LHC machine

Running parameters:

Collision system	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_0$ ($cm^{-2}s^{-1}$)	$<\mathcal{L}>/\mathcal{L}_0$ (%)	Run time (s/year)	σ_{geom} (b)
pp	14.0	10^{34} *		10^7	0.07
PbPb	5.5	10^{27}	70-50	10^6 **	7.7

* $\mathcal{L}_{max}$(ALICE) = 10^{31} ** $\mathcal{L}_{int}$(ALICE) ~ 0.7 nb^{-1}/year

Then, other collision systems:
pA, lighter ions (Sn, Kr, Ar, O)
and lower energies (pp @ 5.5 TeV)

New conditions created at the LHC

Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	850	*1500-3000*
ε (GeV/fm^3)	2.5	4–5	*15–40*
V_f(fm^3)	10^3	$7x10^3$	*$2x10^4$*
τ_{QGP} (fm/c)	<1	1.5–4.0	*4–10*
τ_0 (fm/c)	~1	~0.5	*<0.2*

Formation time τ_0	3 times shorter than RHIC
Lifetime of QGP τ_{QGP}	factor 3 longer than RHIC
Initial energy density ε_0	3-10 higher than RHIC

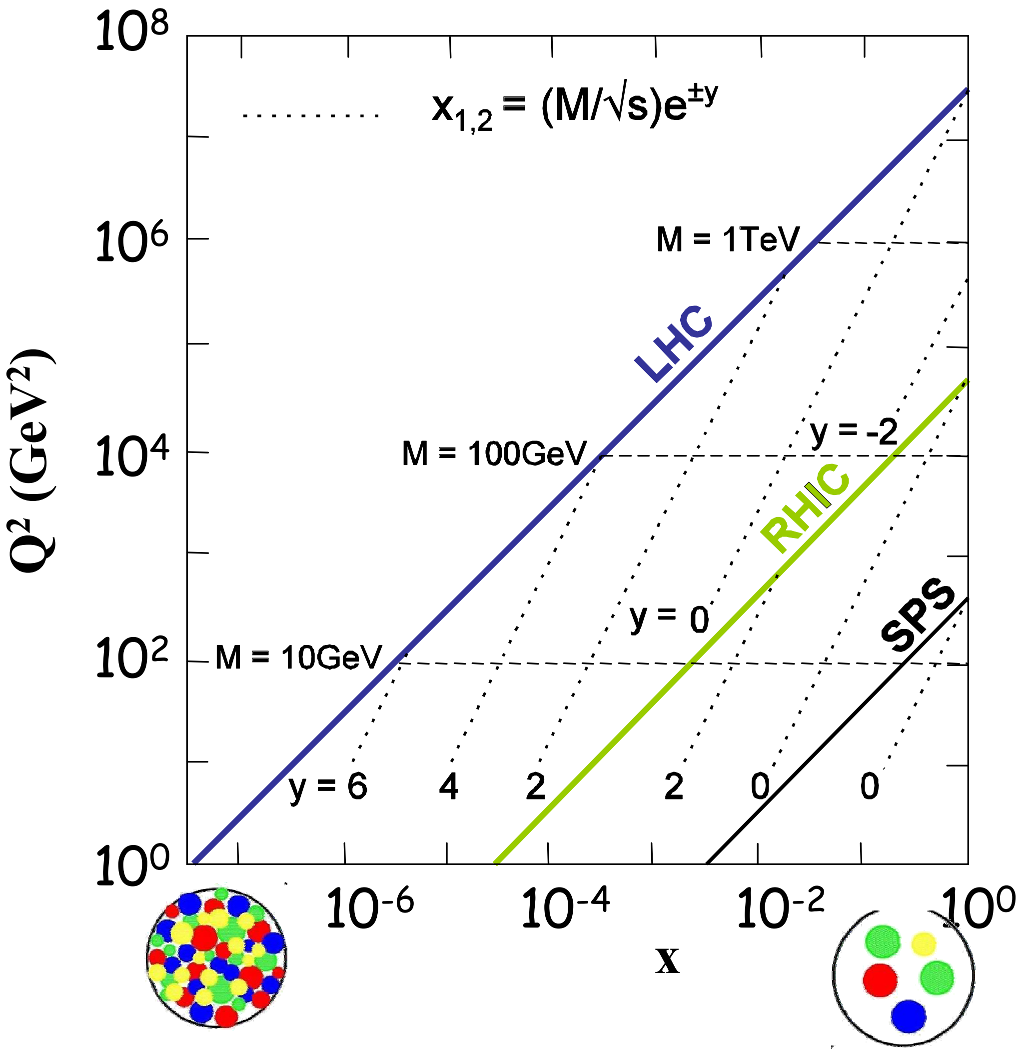
A new kinematic regime

Probe initial partonic state in a new Bjorken-x range (10^{-3}-10^{-5}):

- nuclear shadowing,
- high-density saturated gluon distribution.

Larger saturation scale (Q_S=0.2$A^{1/6}$ $\sqrt{s}^{\delta}$= 2.7 GeV): **particle production dominated by the saturation region.**

The QGP at LHC might evolve from a **Color Glass Condensate** in the initial state of the collision.



… and more hard processes

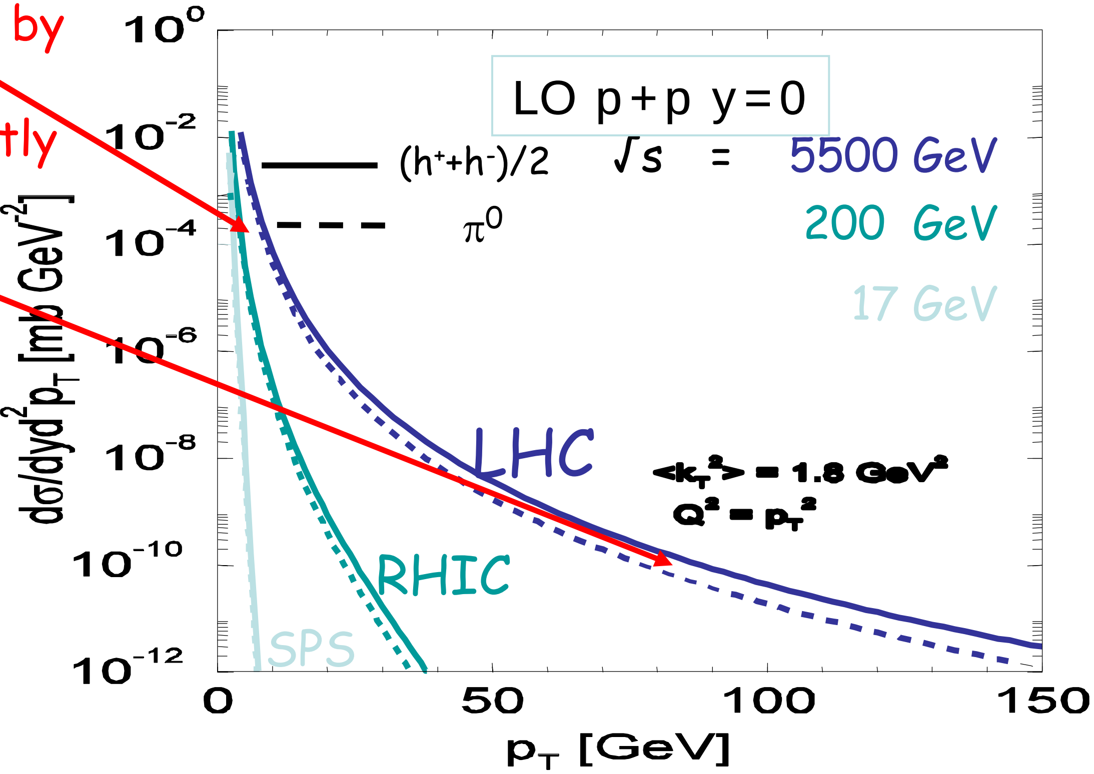
LHC: $\sigma_{hard}/\sigma_{total}$ = 98% (50% at RHIC)

At LHC hard processes contribute significantly to the total AA cross-section.

- Bulk properties are dominated by hard processes
- Very hard probes are abundantly produced.

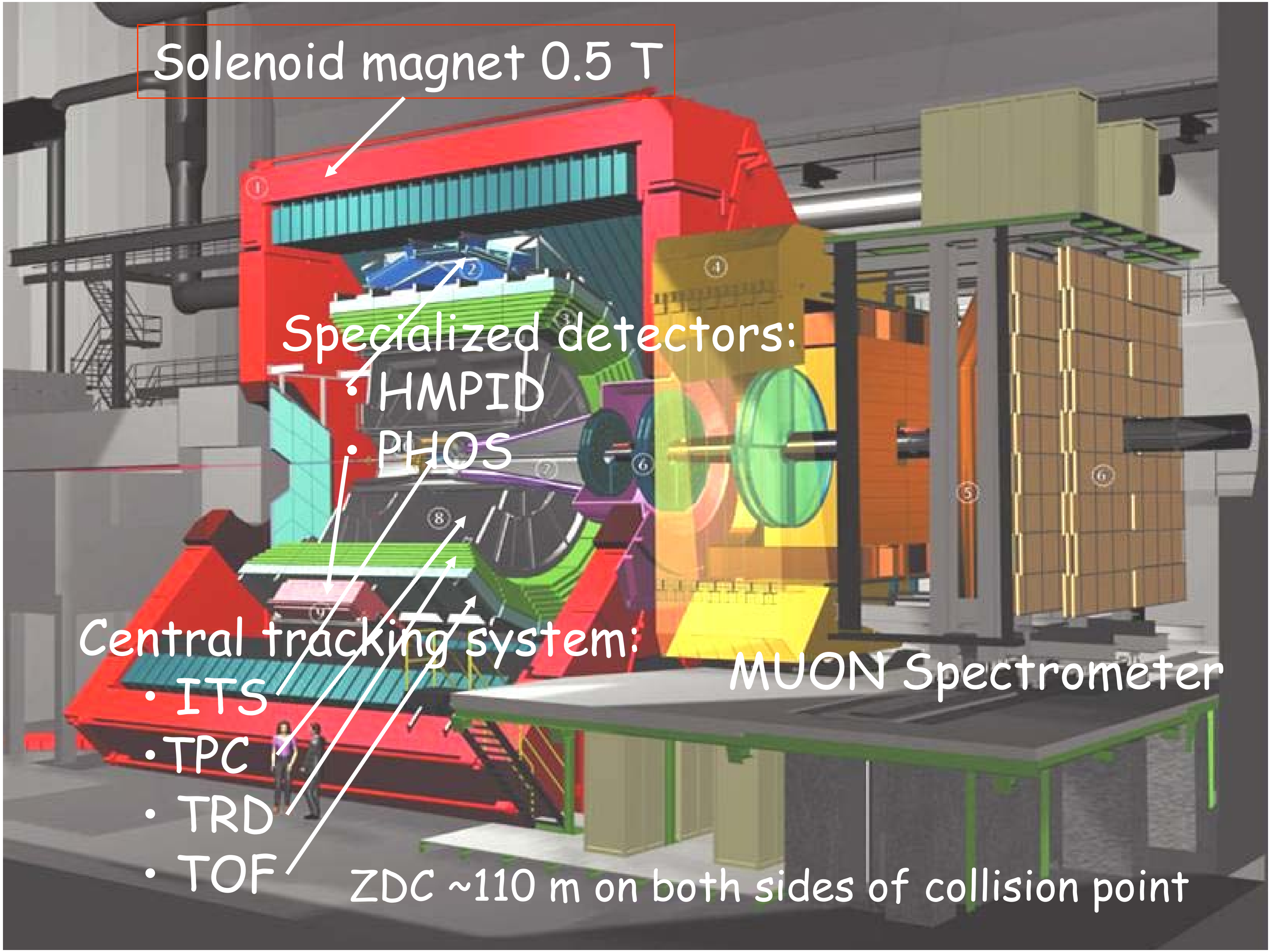
Hard processes are extremely useful tools:

- Probe matter at very early times.
- Hard processes can be calculated by pQCD



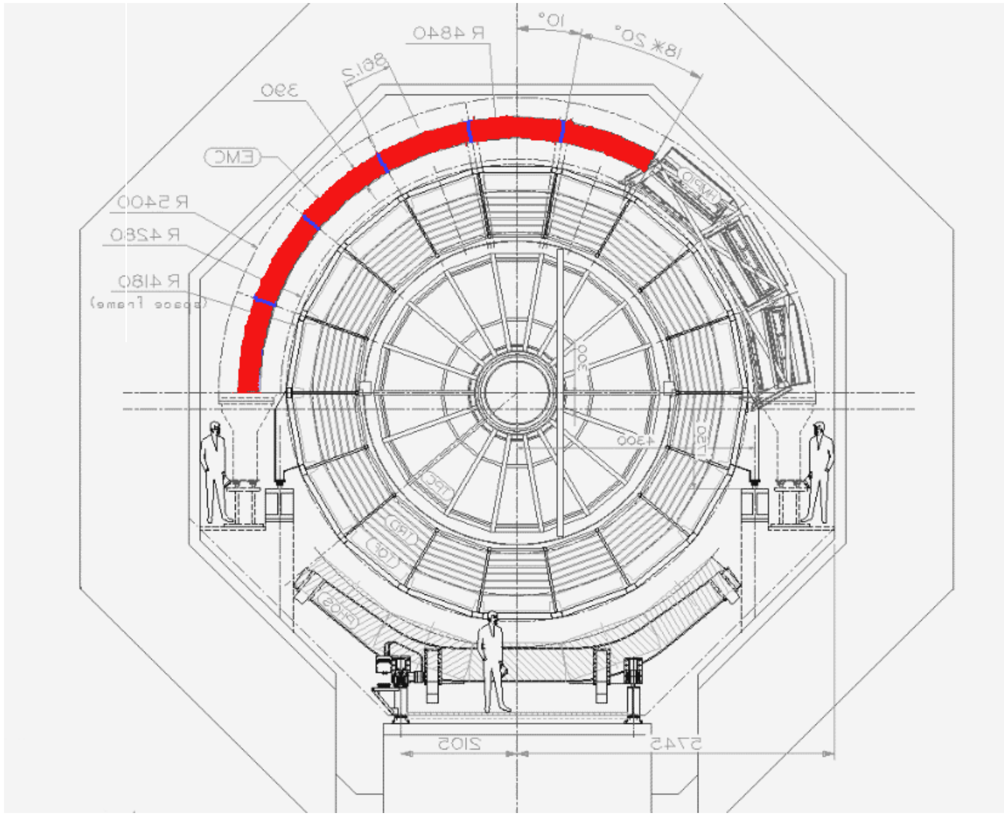
Heavy quarks and weakly interacting probes become accessible

The ALICE experiment


Solenoid magnet 0.5 T
Specialized detectors:
• HMPID
• PHOS
Central tracking system:
• ITS
• TPC
• TRD
• TOF
MUON Spectrometer
ZDC ~110 m on both sides of collision point

Proposed ALICE EMCAL

- **EM Sampling Calorimeter (STAR Design)**
- **Pb-scintillator linear response**
  - **$-0.7 < \eta < 0.7$**
  - $60° < \Phi < 180°$
- **Energy resolution ~15%/$\sqrt{E}$**



The ALICE features

With its system of detectors ALICE will meet the challenge to measure event-by-event the flavour content and the phase-space distribution of highly populated events produced by heavy ion collisions:

- Most (2π * 1.8 units of η) of the hadrons (dE/dx + TOF), leptons (dE/dx, transition radiation, magnetic analysis) and photons (high resolution EM calorimetry).

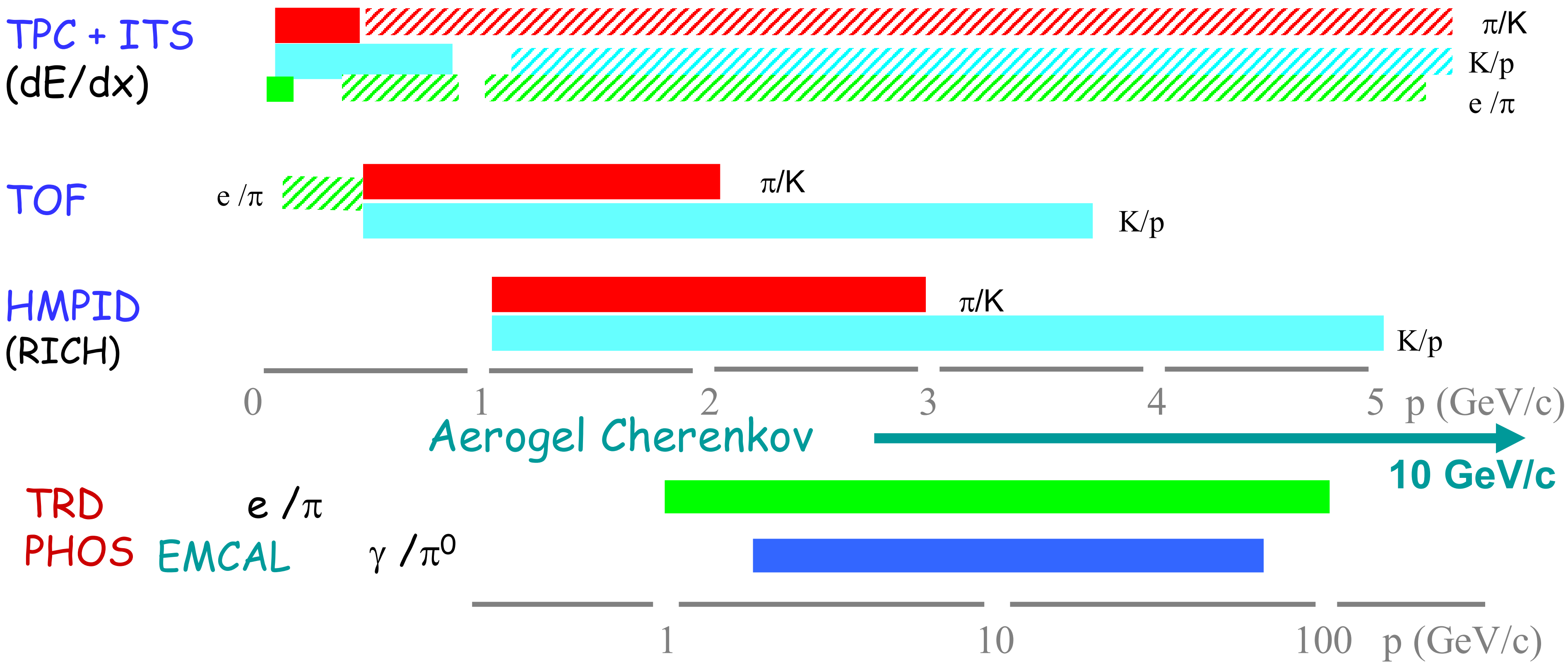
- Track and identify from very low p_t (~ 100 MeV/c; soft processes) up to very high p_t (>100 GeV/c; hard processes).

- Identify short lived particles (hyperons, D/B meson) through secondary vertex detection.

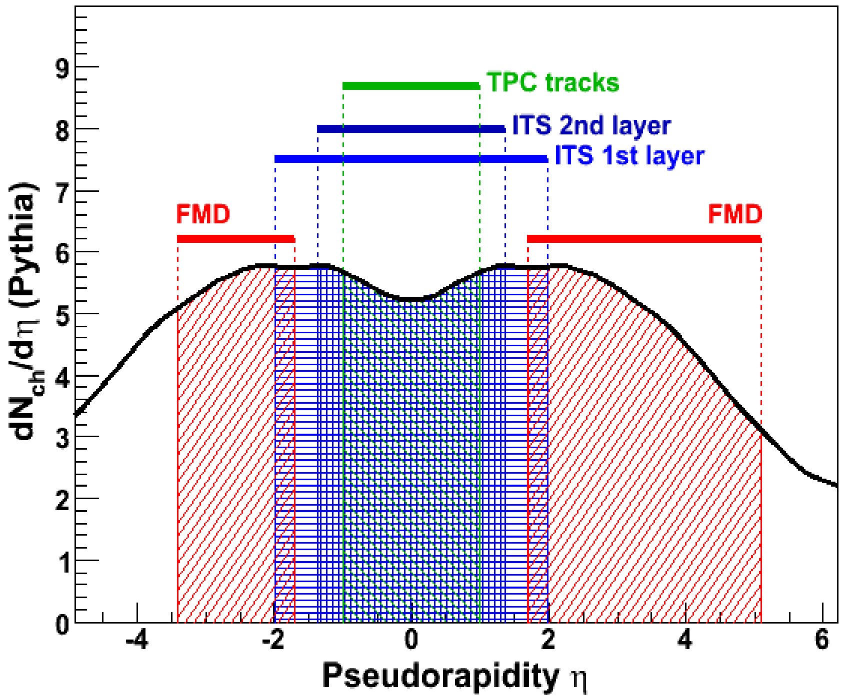
- Identify jets.

ALICE Particle Identification

Alice uses ~ all known techniques!



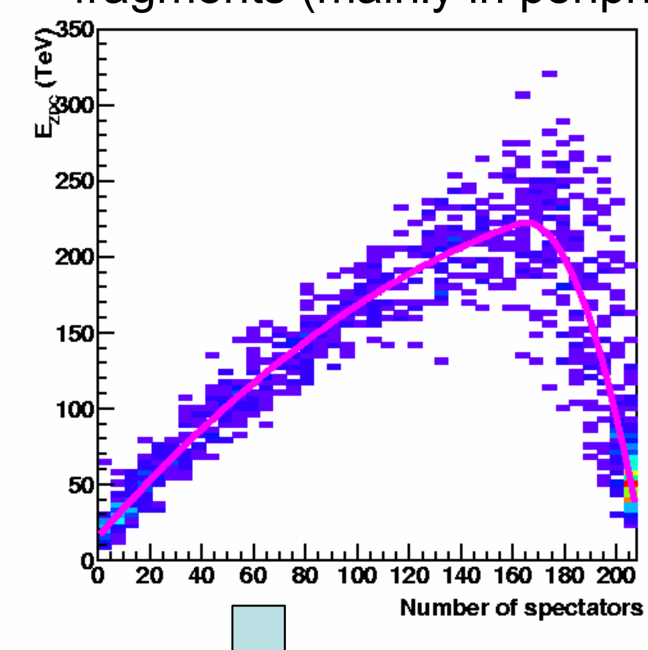
ALICE pseudorapidity coverage for multiplicity measurements

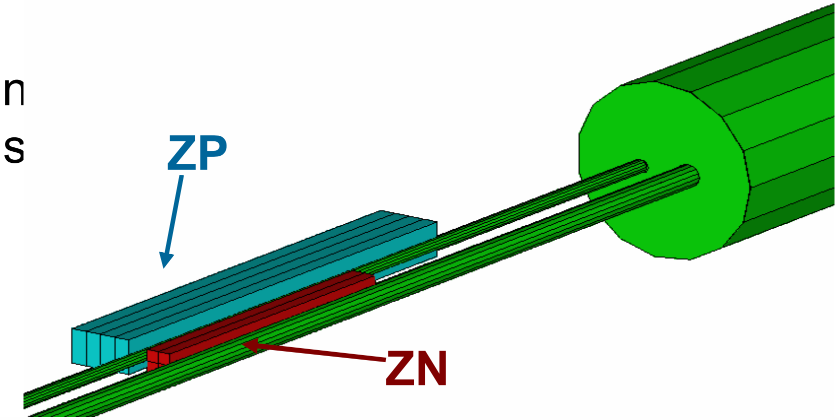


- Different multiplicity measurement techniques
  - CLUSTERS on innermost ITS layers (Silicon Pixels)
  - TRACKLETS with 2 innemost layers of ITS (Silicon Pixels)
  - FULL TRACKING (ITS+TPC)
  - ENERGY DEPOSITION in the pads of Forward Multiplicity Detector (FMD)

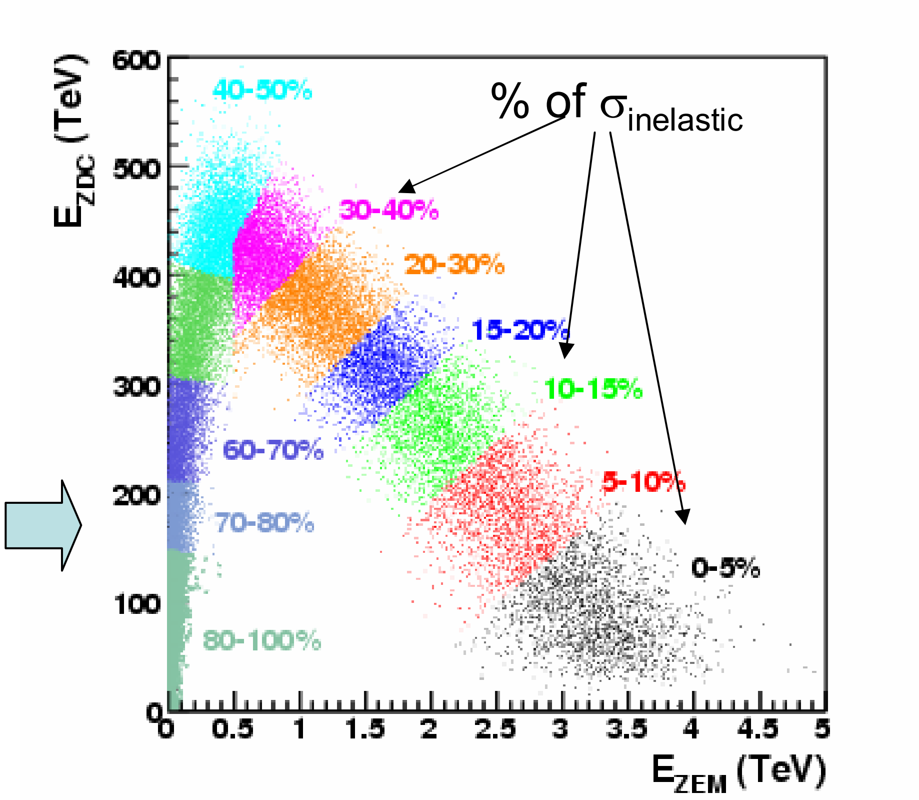
ZDC and centrality determination

- E_{ZDC} correlated with number of spectators BUT two branches in the correlation
  - Break-up of correlation due to production fragments (mainly in peripheral collisions





- ZEM needed to solve the ambiguity
  - Signal with relatively low resolution, but whose amplitude increases monotonically with centrality



ALICE Physics Goals

- Event characterization in the new energy domain (for PbPb but also for pp)
  - multiplicity, η distributions, centrality
- Bulk properties of the hot and dense medium, dynamics of hadronization
  - chemical composition, hadron ratios and spectra, dilepton continuum, direct photons
- Expansion dynamics, space-time structure
  - radial and anisotropic flow, momentum (HBT) correlations
- Deconfinement:
  - charmonium and bottomonium spectroscopy
- Energy loss of partons in quark gluon plasma:
  - jet quenching, high p_t spectra
  - open charm and open beauty
- Chiral symmetry restoration:
  - neutral to charged ratios
  - resonance decays
- Fluctuation phenomena, critical behavior:
  - event-by-event particle composition and spectra

Highlights on physics topics - 1

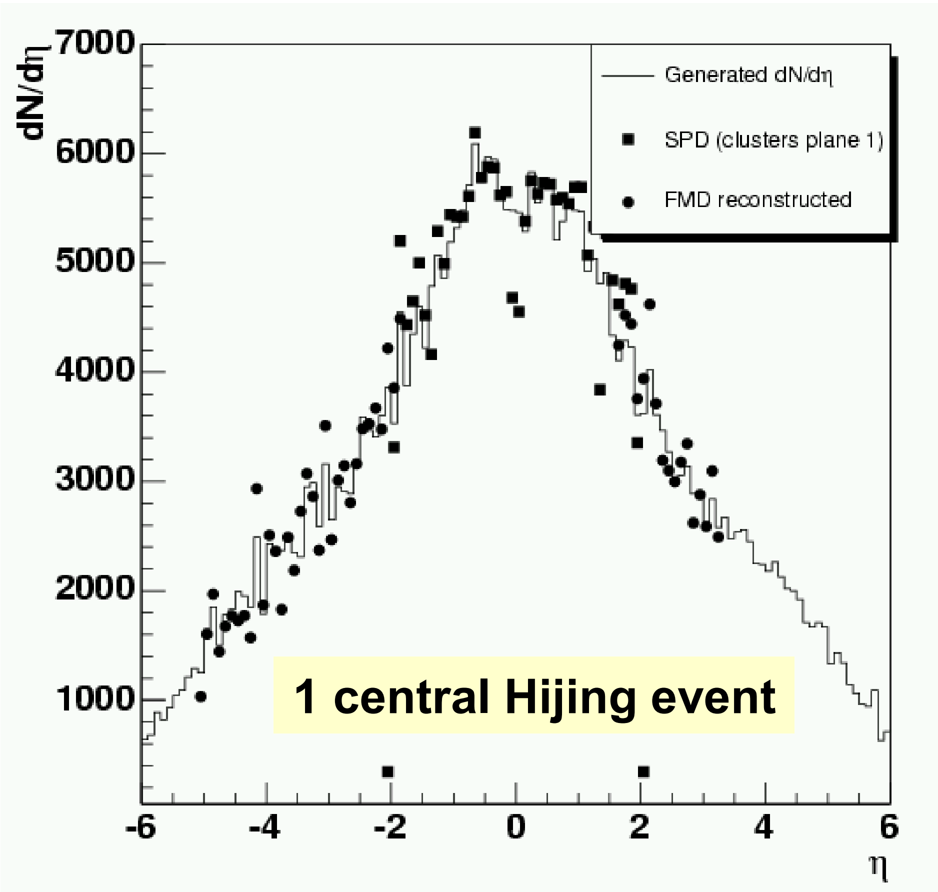
Soft Physics

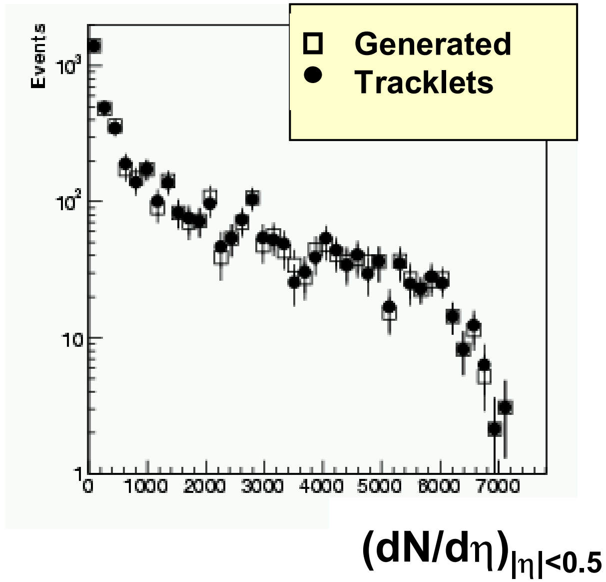
Global event properties in Pb-Pb

Multiplicity distribution ($dN_{ch}/d\eta$) in Pb-Pb

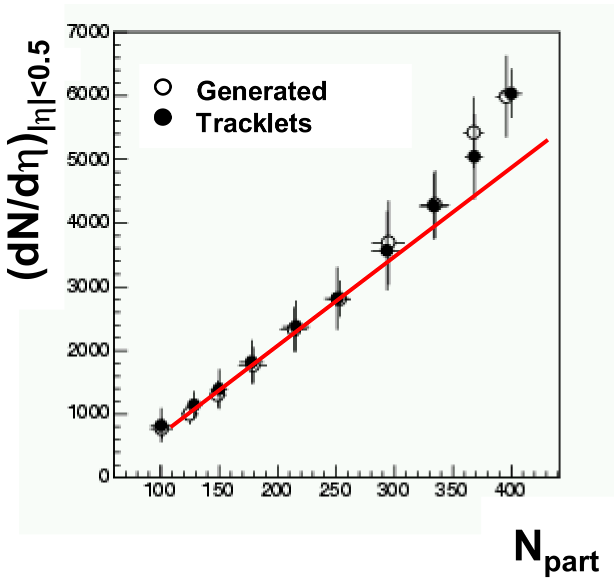
➡ **Energy density**

Silicon Pixel Detector (SPD) : $-1.6 < \eta < +1.6$
+ Forward Multiplicity Detector (FMD): $\eta \longrightarrow -5, +3.5$





dN/dη vs centrality (N_{part}) ➡ Fraction of particles produced in hard processes



Identified particle spectra

Equilibrium vs non-equilibrium
Statistical models

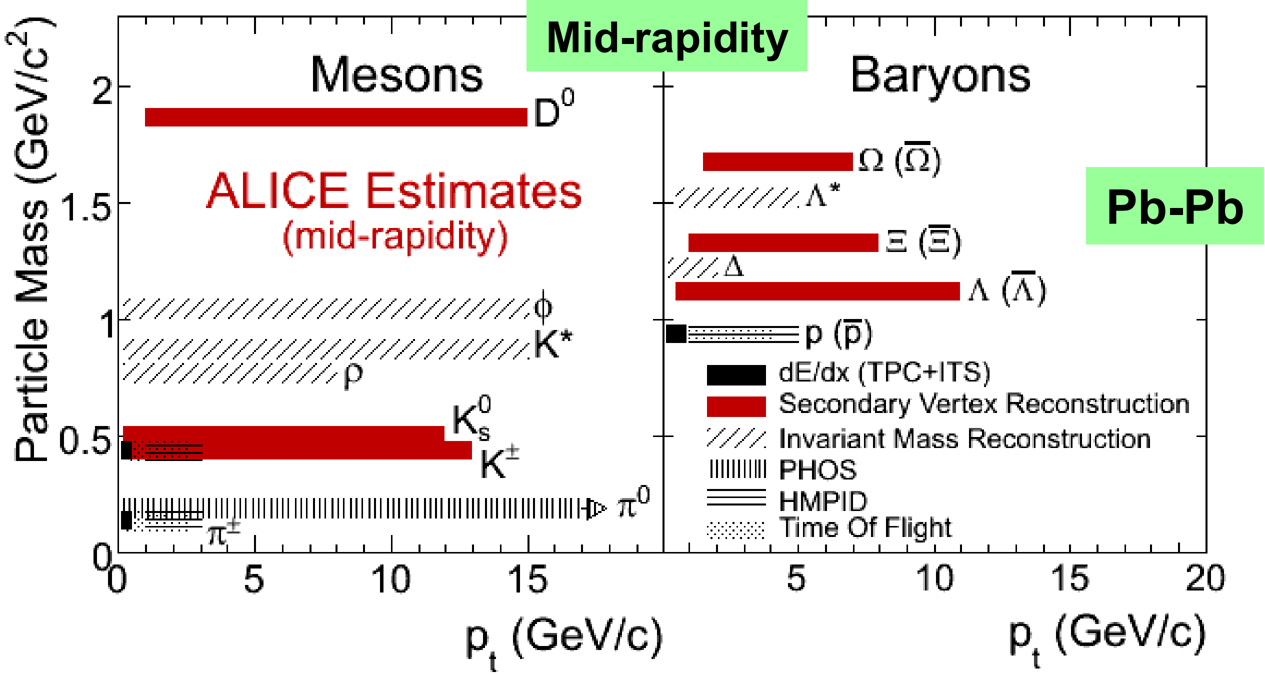
Chemical composition, particle ratios

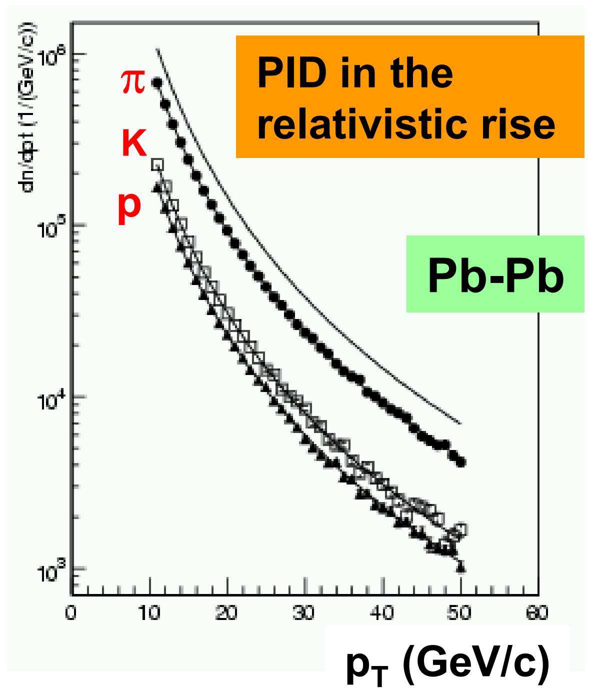
Interplay between hard and soft processes at intermediate p_T : parton recombination+fragmentation?

R_{cp}: central over peripheral yields/<N_{bin}>
Baryon/meson ratio
Elliptic flow v_2

p_T range (PID or stat. limits) for 1 year: 10^7 central Pb-Pb and 10^9 min. bias pp

π, K, p: 0.1- 0.15 up to 50 GeV
Weak or strong decaying particles: up to 10-15 GeV



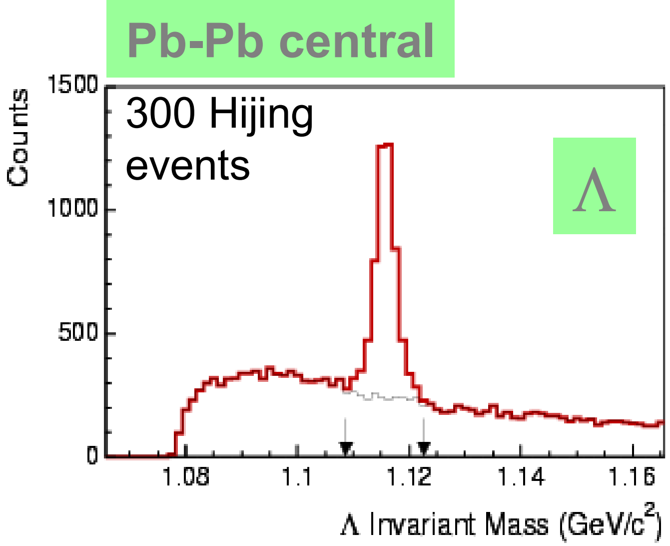


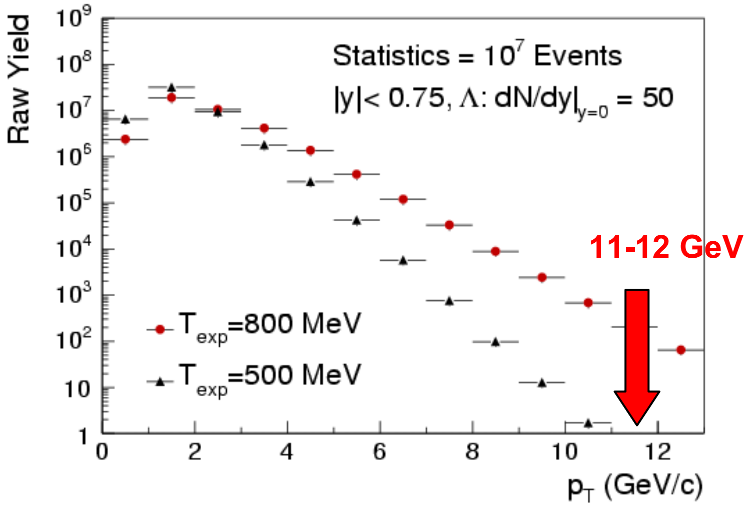
Topological identification of strange particles

Statistical limit : p_T ~ 11 - 13 GeV for K^+, K^-, K^0_s, Λ; 7 - 10 GeV for Ξ, Ω

Secondary vertex and cascade finding

p_T dependent cuts -> optimize efficiency over the whole p_T range

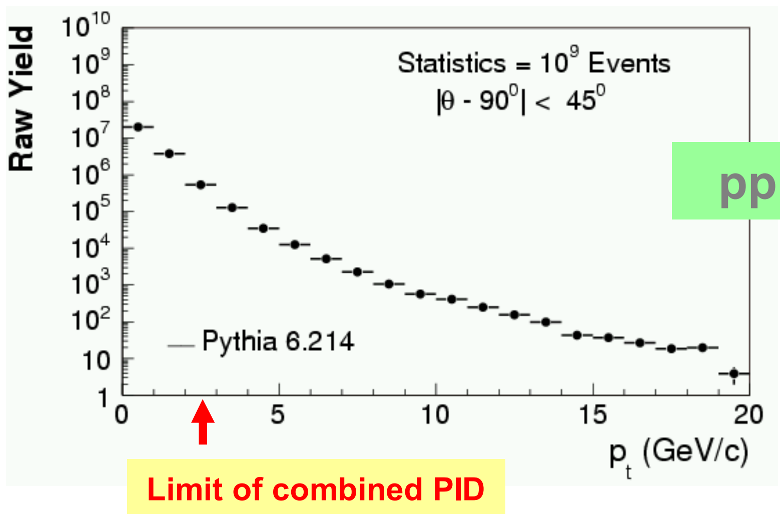




Reconst. Rates:

- Λ: 13 /event
- Ξ: 0.1 /event
- Ω: 0.01 /event

Identification of K^+, K^- via their kink topology $K \rightarrow \mu\nu$

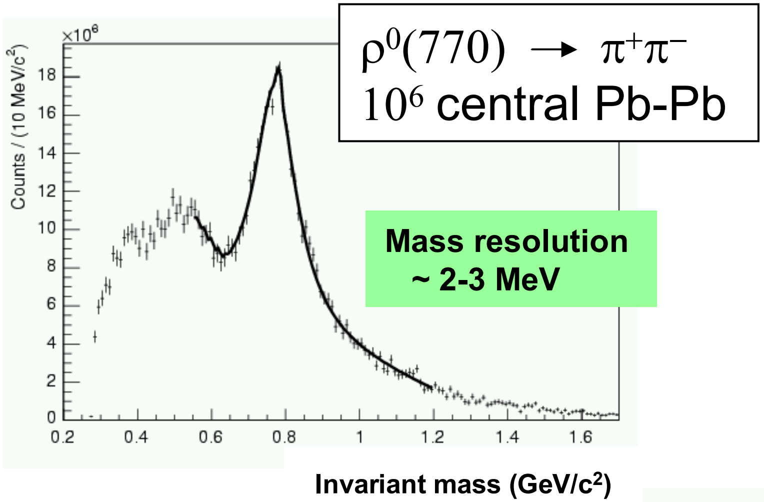


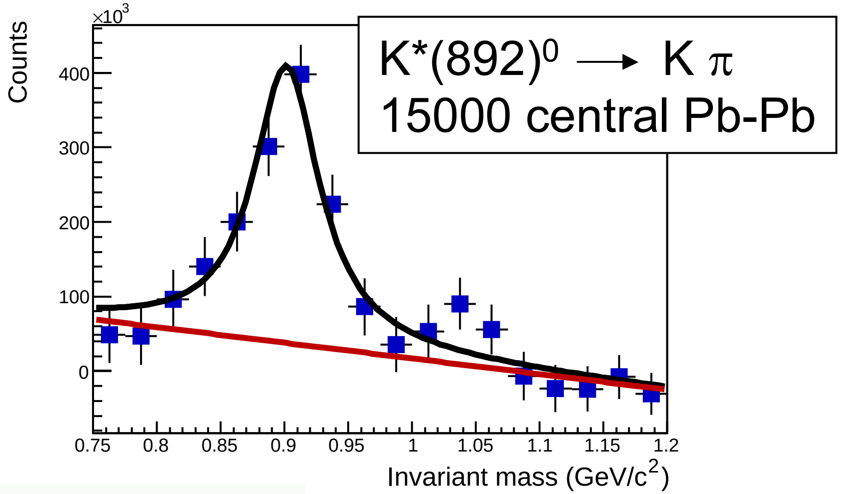
pp collisions

Resonances (ρ, ϕ, K*, …)

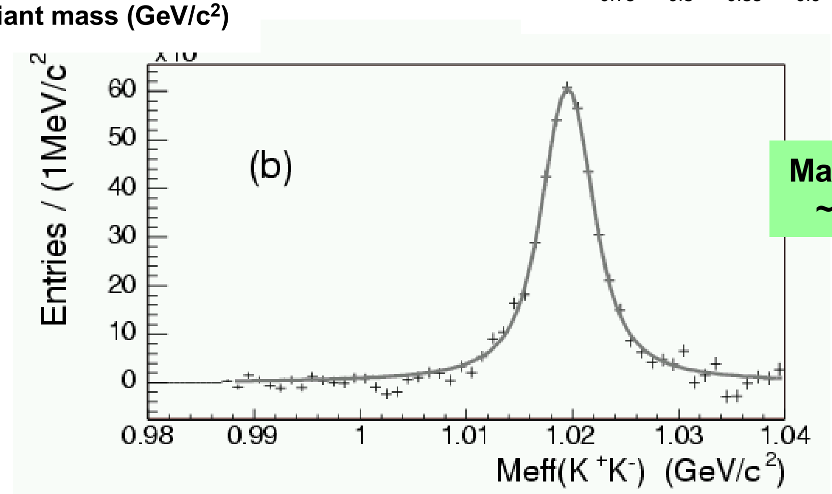
- Time difference between chemical and kinetic freeze-out
- In medium modifications of mass, width, comparison between hadronic and leptonic channels ➡ partial chiral symmetry restoration

Invariant mass reconstruction, background subtracted (like-sign method)
➡ mass resolutions ~ 1.5 - 3 MeV and p_T stat. limits from 8 (ρ) to 15 GeV (ϕ,K*)





$\phi\,(1020) \rightarrow K^+K^-$



Mass resolution ~ 1.2 MeV

Anisotropic Flow

At LHC: v_2 values of 5-10% are predicted => measurements easy
But non-flow contributions from (mini-) jets expected to obscure the flow signal
=> important to compare different methods, use multi-particle correlations
Relation between v_2 and higher harmonics (v_4, v_6, …) to test perfect liquid vs viscous fluid

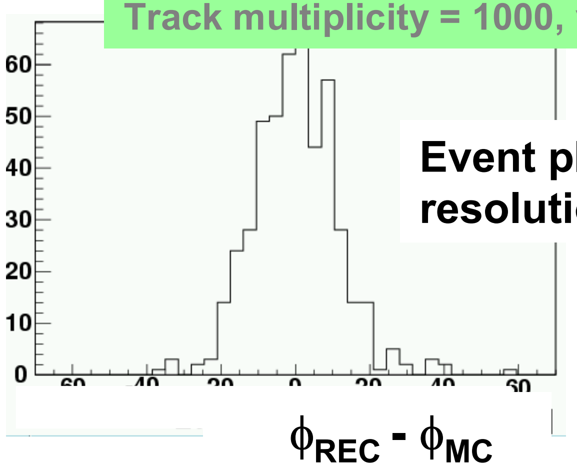
Performance of event plane method

$v_n = \langle \cos[n(\phi - \phi_R)] \rangle$ / ev.plane resolution

Various independent estimates of reaction plane and v_n from different regions of phase space

Measurements with:
TPC/ITS, SPD (pixels) and forward detectors (FMD, PMD)

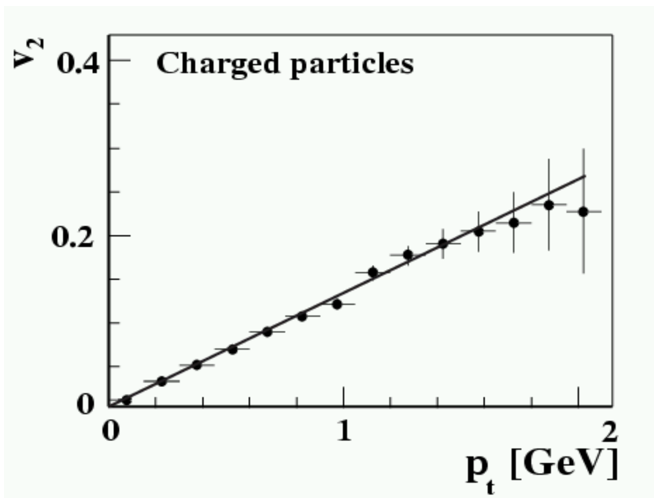
Track multiplicity = 1000, v_2 = 0.06

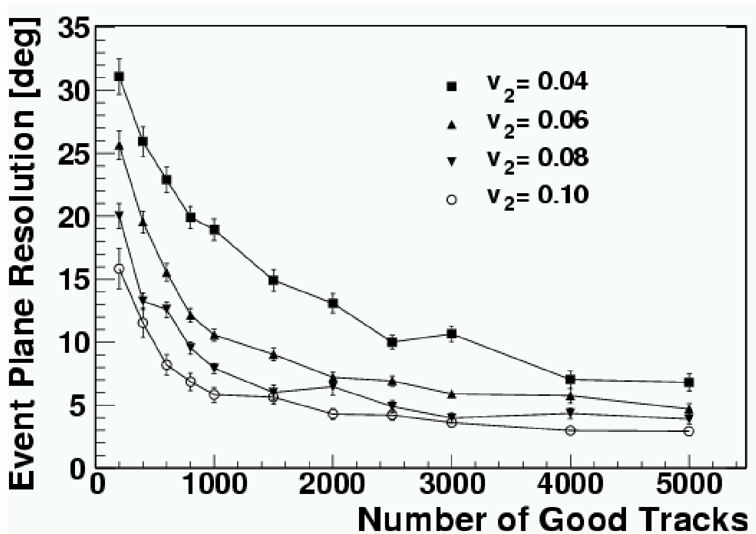


Event plane resolution ~ 10°

TPC

Generated vs reconstructed v_2
100 Pb-Pb events
2000 tracks/event





Highlights on physics topics - 2

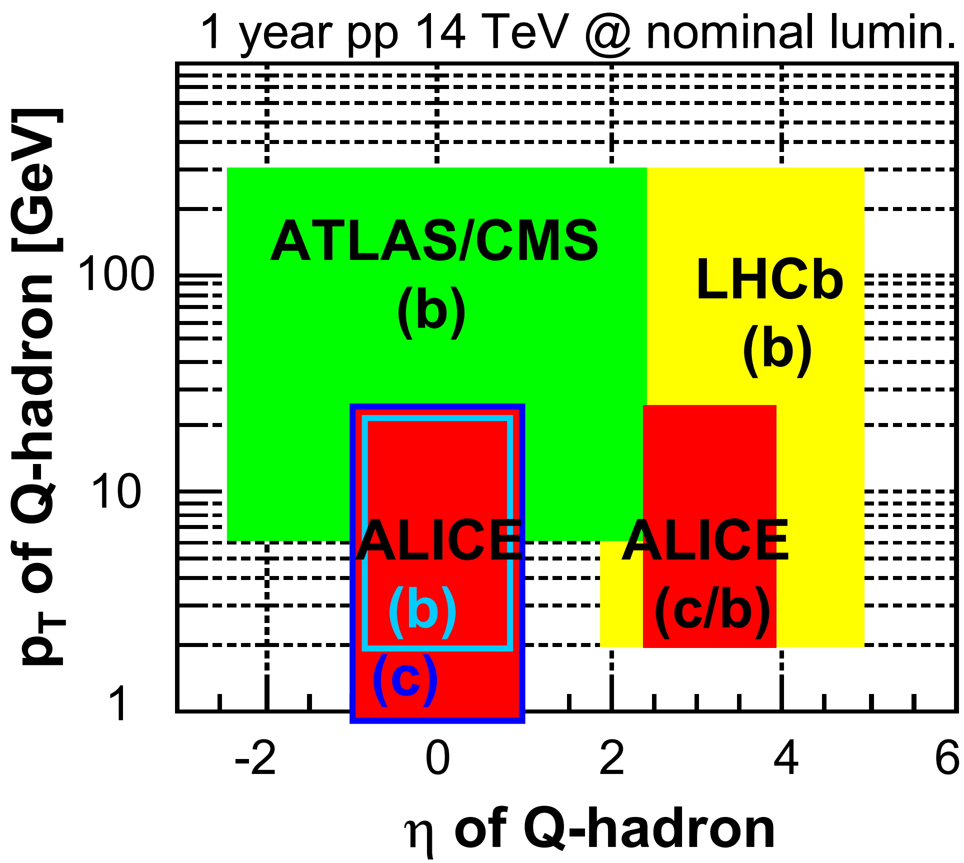
Heavy flavours and quarkonia

Heavy Flavour physics in ALICE: motivations

- **Energy loss of Heavy Quarks (HQ) in hot and high density medium** formed in AA central collisions.
- **Brownian motion** and **coalescence of low p_T HQ** in the quark gluon plasma (QGP).
- **Dissociation (and regeneration) of quarkonia in hot QGP**.
- Heavy flavour physics in **pp collisions**: small x physics, pQCD, HQ fragmentation functions, gluon shadowing, quarkonia production mechanism.

Heavy-flavours in ALICE

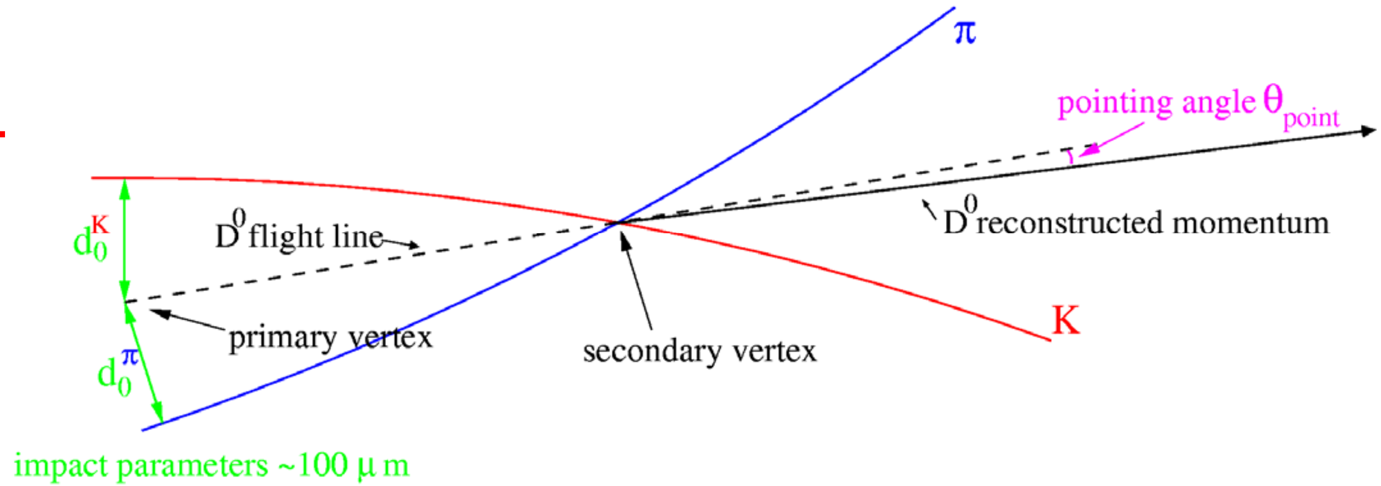
- ALICE can study several channels:
  - hadronic ($|\eta|<0.9$)
  - electronic ($|\eta|<0.9$)
  - muonic ($-4 < \eta < -2.5$)
- ALICE coverage:
  - low-p_T region (down to $p_t \sim 0$ for charm)
  - central and forward rapidity regions
- High precision vertexing in the central region to identify D ($c\tau \sim$ 100-300 mm) and B ($c\tau \sim$ 500 mm) decays



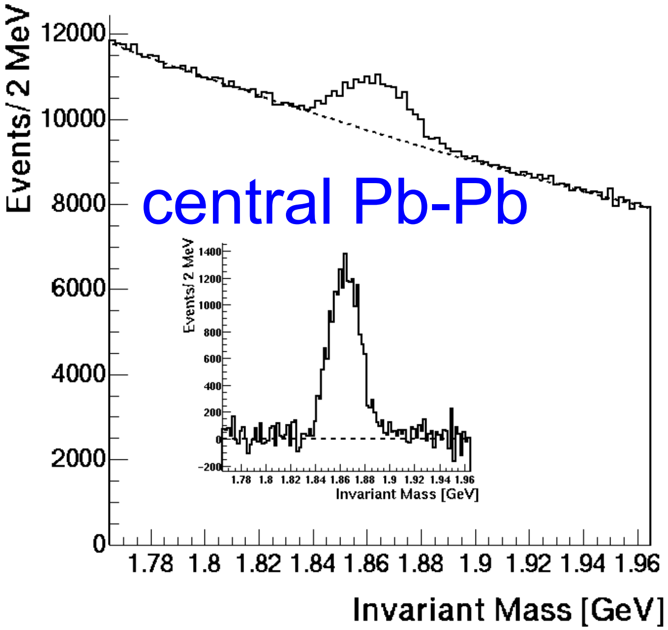
Hadronic decays of D mesons

- **No dedicated trigger in the central barrel** → extract the signal from Minimum Bias events
  - Large combinatorial background (benchmark study with $dN_{ch}/dy = 6000$ in central Pb-Pb!)
- **SELECTION STRATEGY**: invariant-mass analysis of fully-reconstructed topologies originating from **displaced vertices**
  - build pairs/triplets/quadruplets of tracks with **correct combination of charge signs** and **large impact parameters**
  - **particle identification** to tag the decay products
  - calculate the **vertex (DCA point)** of the tracks
  - requested a **good pointing** of reconstructed D momentum to the primary vertex

$D^0 \to K^- \pi^+$



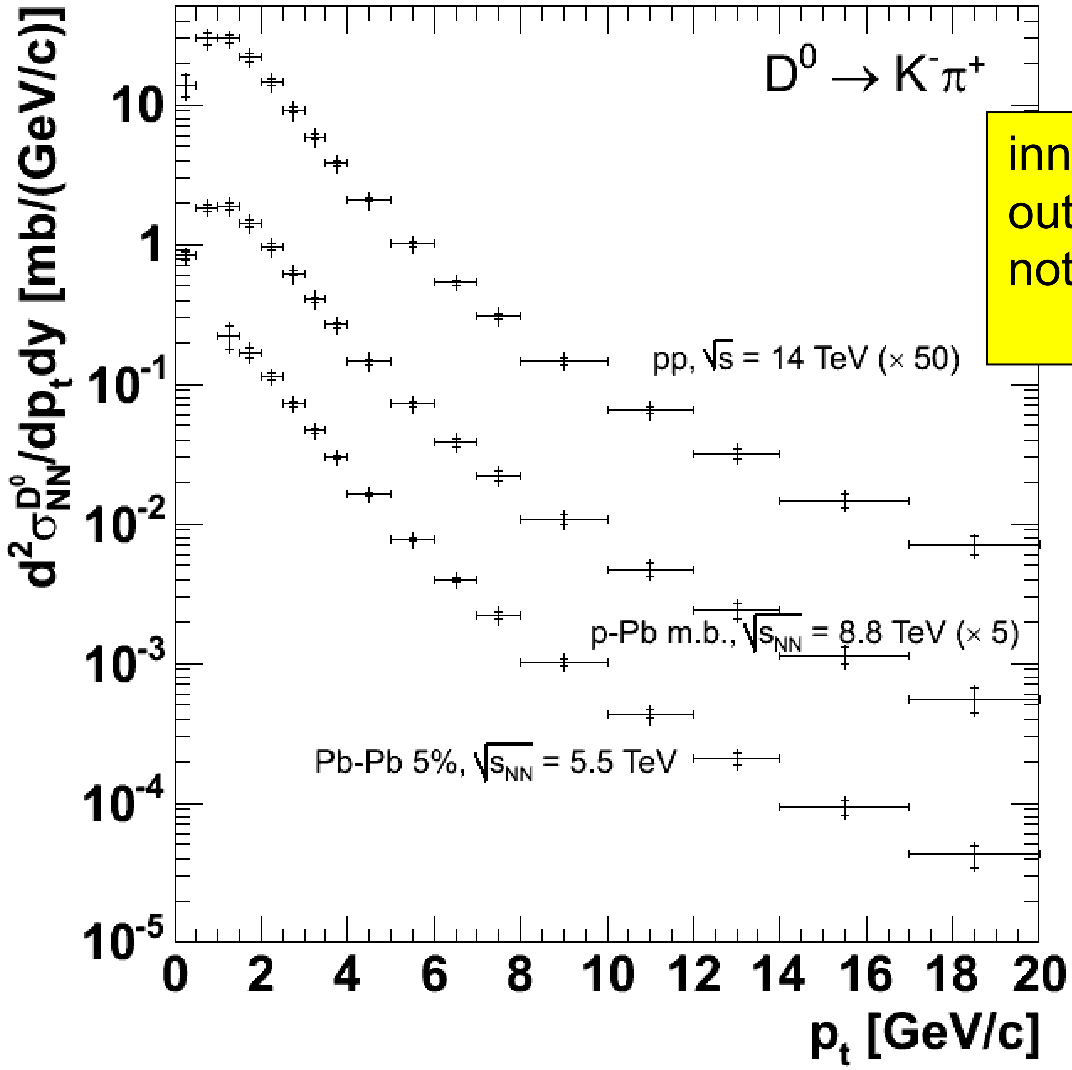
$D^0 \rightarrow K^- \pi^+$: results (I)



	S/B initial (M±3σ)	S/B final (M±1σ)	Significance $S/\sqrt{S+B}$ (M±1σ)
Pb-Pb Central (dN_{ch}/dy = 6000)	$5 \cdot 10^{-6}$	**10%**	**~35 (for 10^7 evts, ~1 month)**
pPb min. bias	$2 \cdot 10^{-3}$	**5%**	**~30 (for 10^8 evts, ~1 month)**
pp	$2 \cdot 10^{-3}$	**10%**	**~40 (for 10^9 evts, ~7 months)**

With dN_{ch}/dy = 3000 in Pb-Pb, S/B larger by × 4 and significance larger by × 2

$D^0 \rightarrow K^- \pi^+$: results (II)



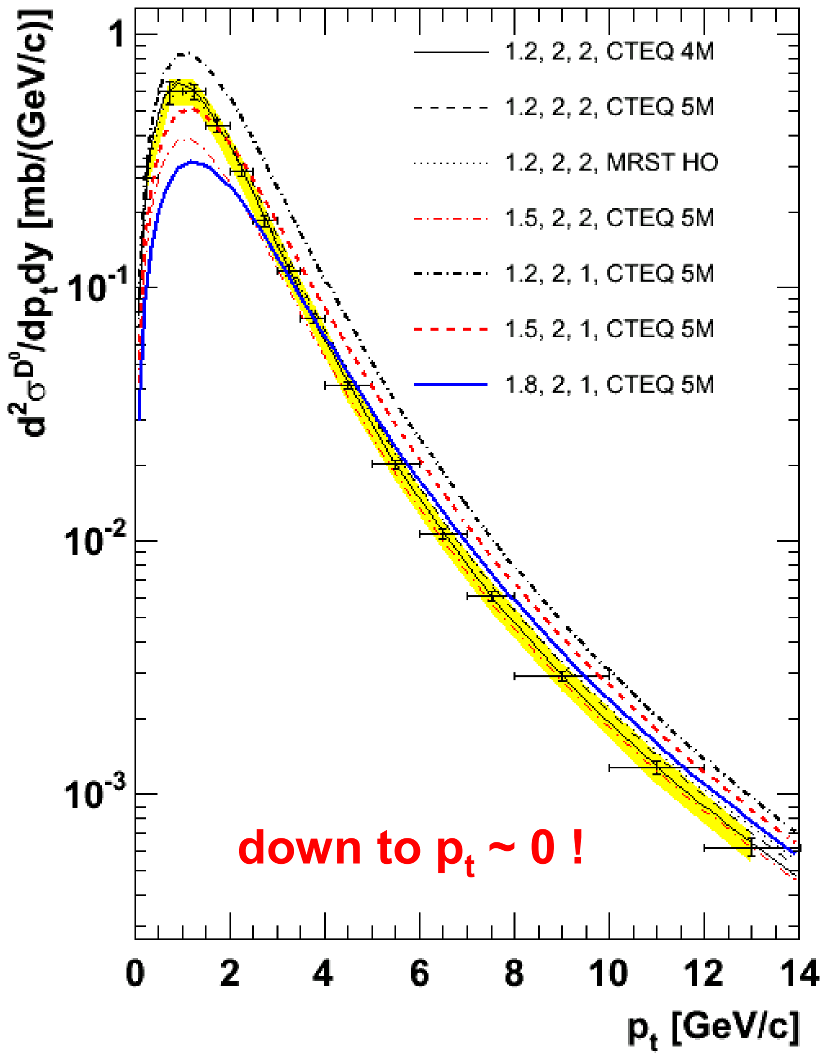
inner bars: stat. errors
outer bars: stat. ⊕ p_t-dep. syst.
not shown: 9% (Pb-Pb), 5% (pp, p-Pb) normalization errors

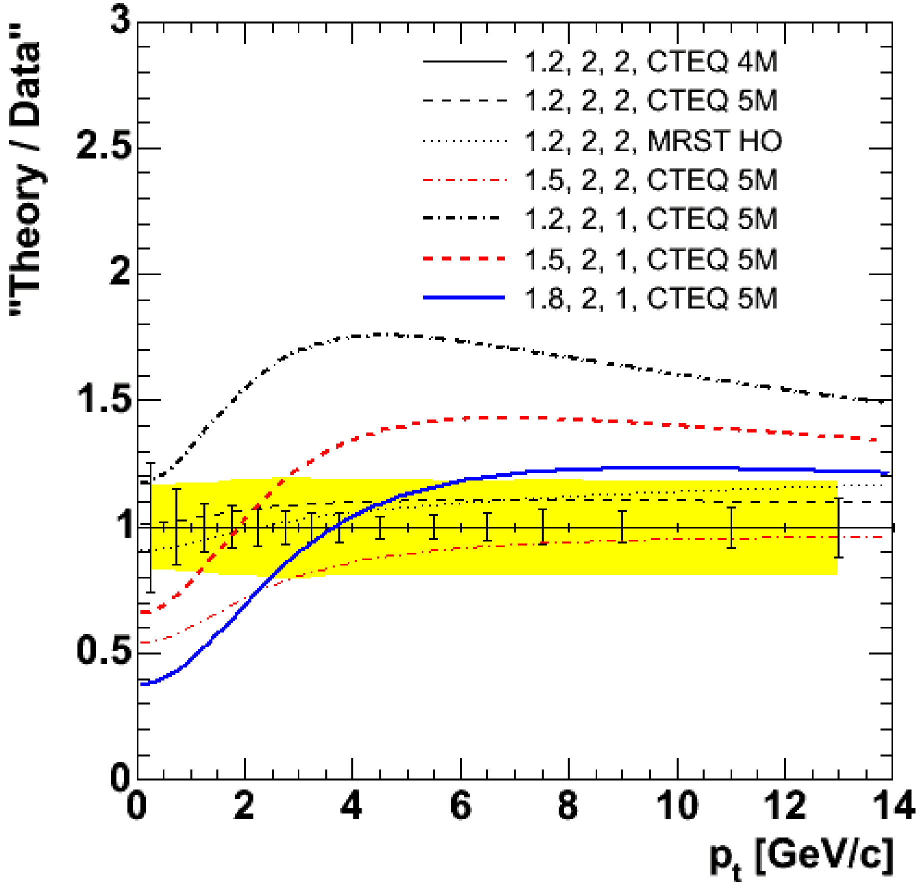
1 year at nominal luminosity
(10^7 central Pb-Pb events,
10^9 pp events)
+ 1 year with 1month of p-Pb running
(10^8 p-Pb events)

➡ Down to p_t ~ 0 in pp and p-Pb (1 GeV/c in Pb-Pb)
→important to go to low p_T for charm cross-section measurement

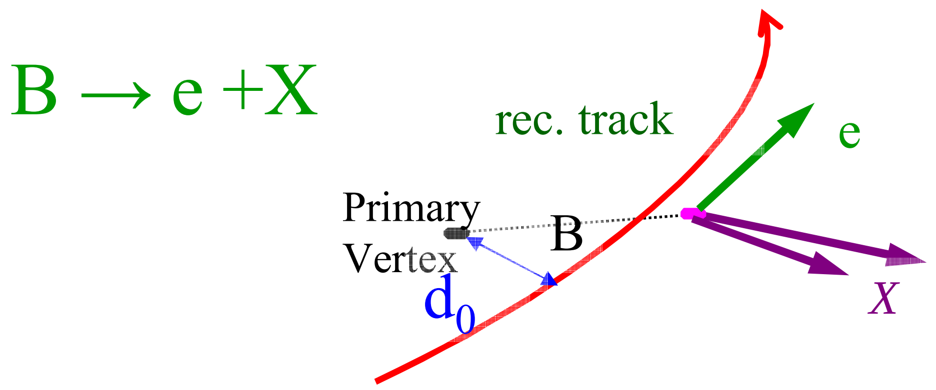
Open charm in pp ($D^0 \rightarrow K\pi$)
Sensitivity to NLO pQCD params

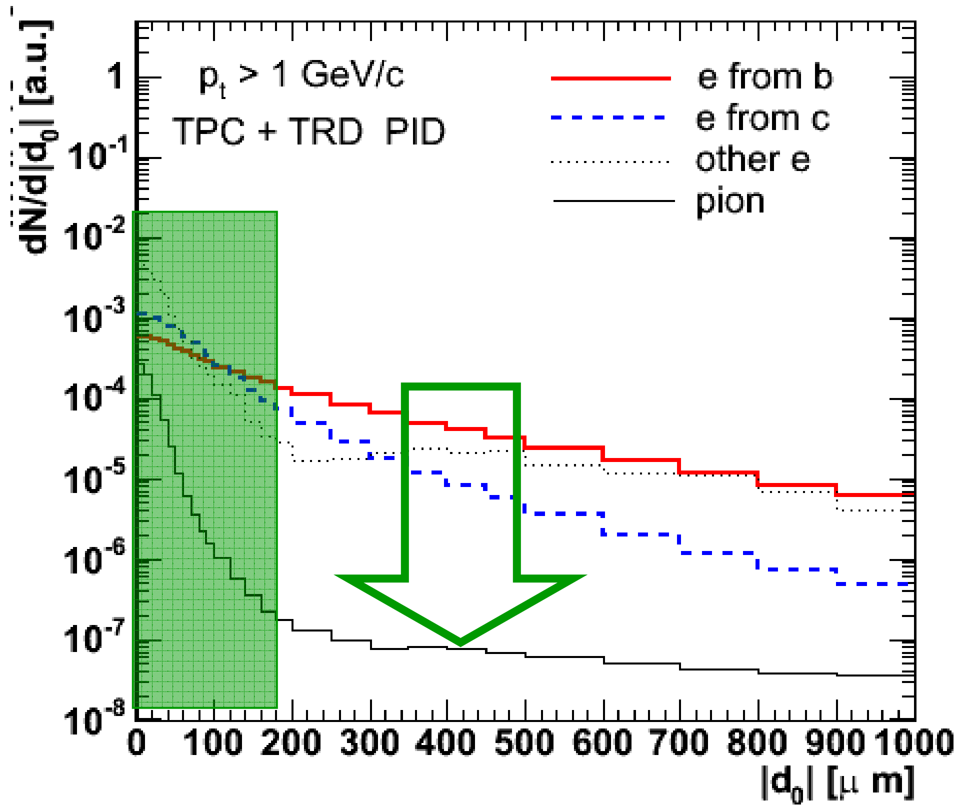
$\sqrt{s}$ = 14 TeV





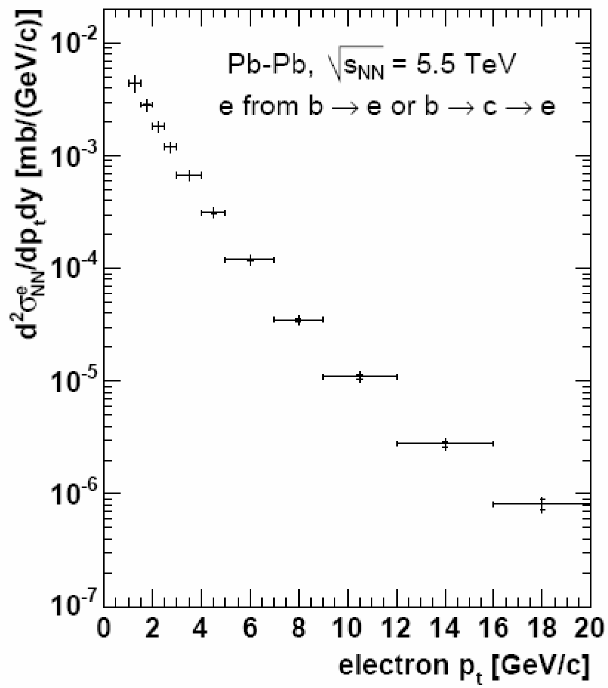
Open Beauty from single electrons





STRATEGY

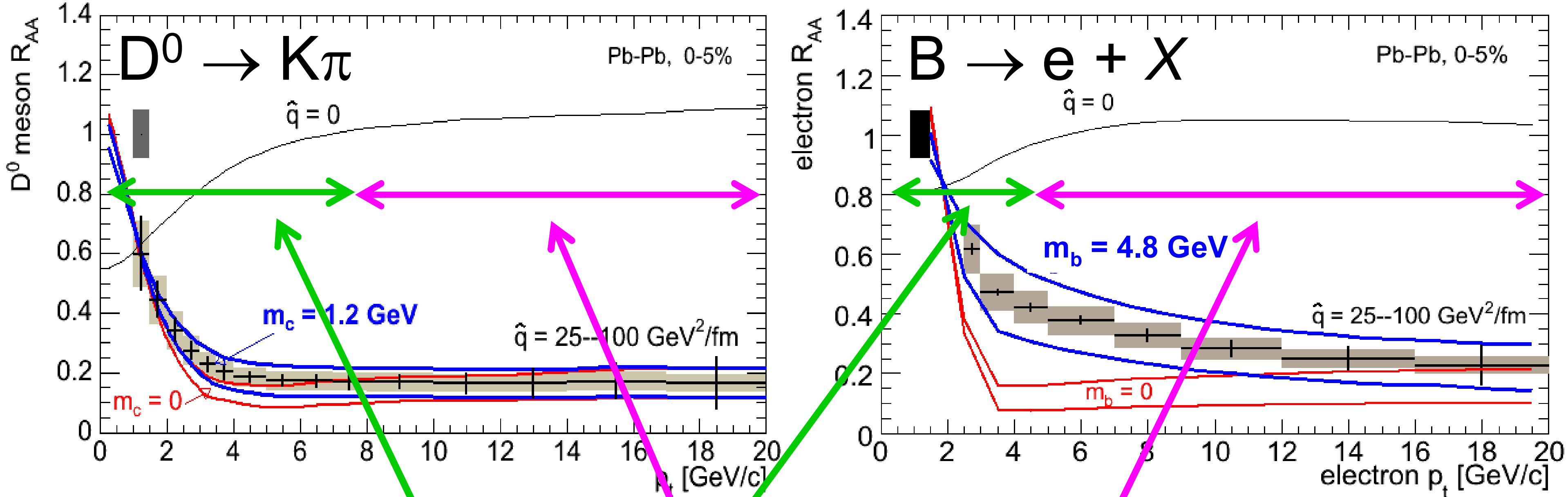
- Electron Identification (TRD+TPC): reject most of the hadrons
- Impact parameter cut: high precision vertexing in ITS: reduce charm and bkg electrons
- Subtraction of the residual background



Charm and Beauty Energy Loss : R_{AA}

$$R^{D}_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{D}_{AA}/dp_t}{dN^{D}_{pp}/dp_t}$$

$$R^{e}_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{e}_{AA}/dp_t}{dN^{e}_{pp}/dp_t}$$



Low p_t (< 6–7 GeV/c)
Also nuclear shadowing (here EKS98)

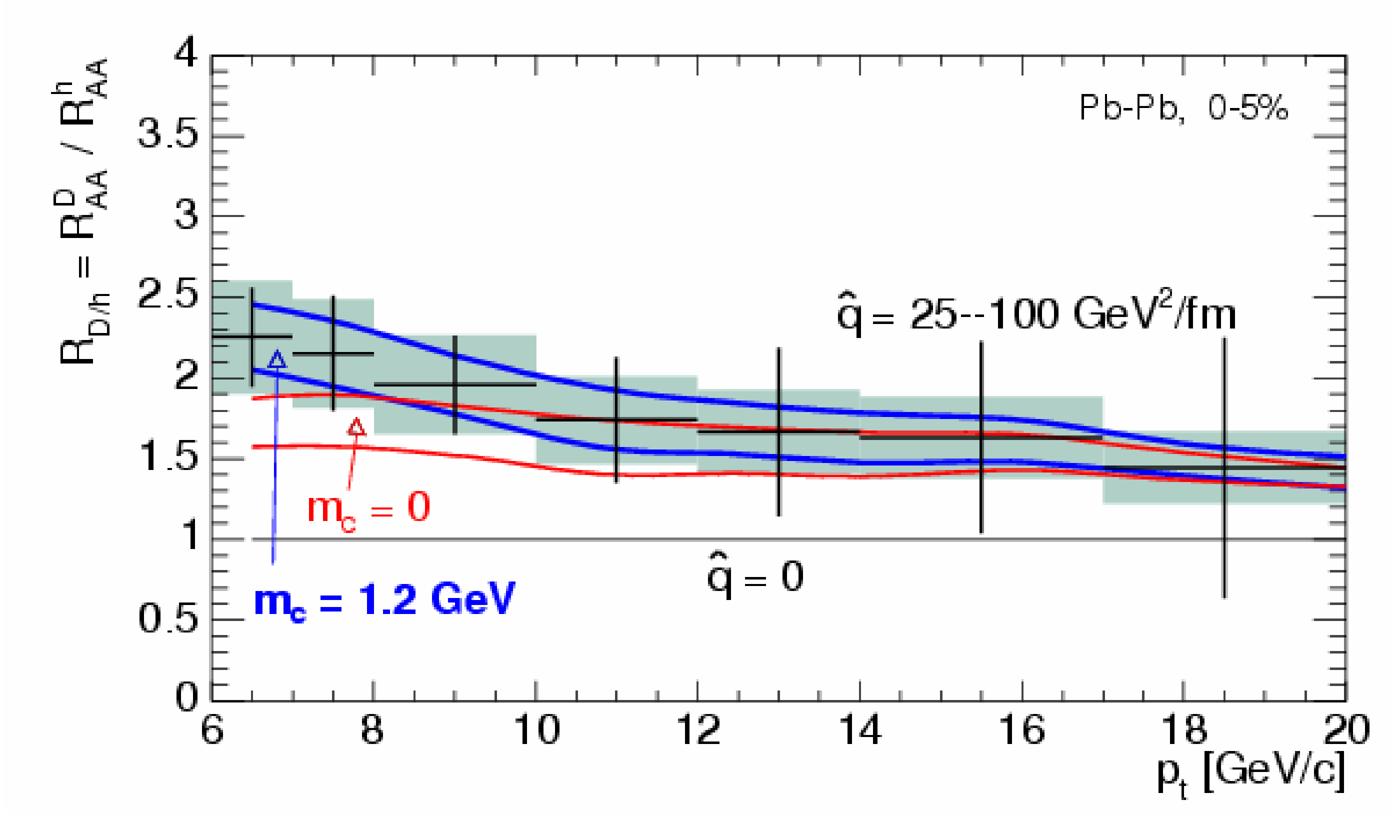
High p_t (> 6–7 GeV/c)
Only parton energy loss

1 year at nominal luminosity
(10^7 central Pb-Pb events, 10^9 pp events)

Heavy-to-light ratios in ALICE

For charm:

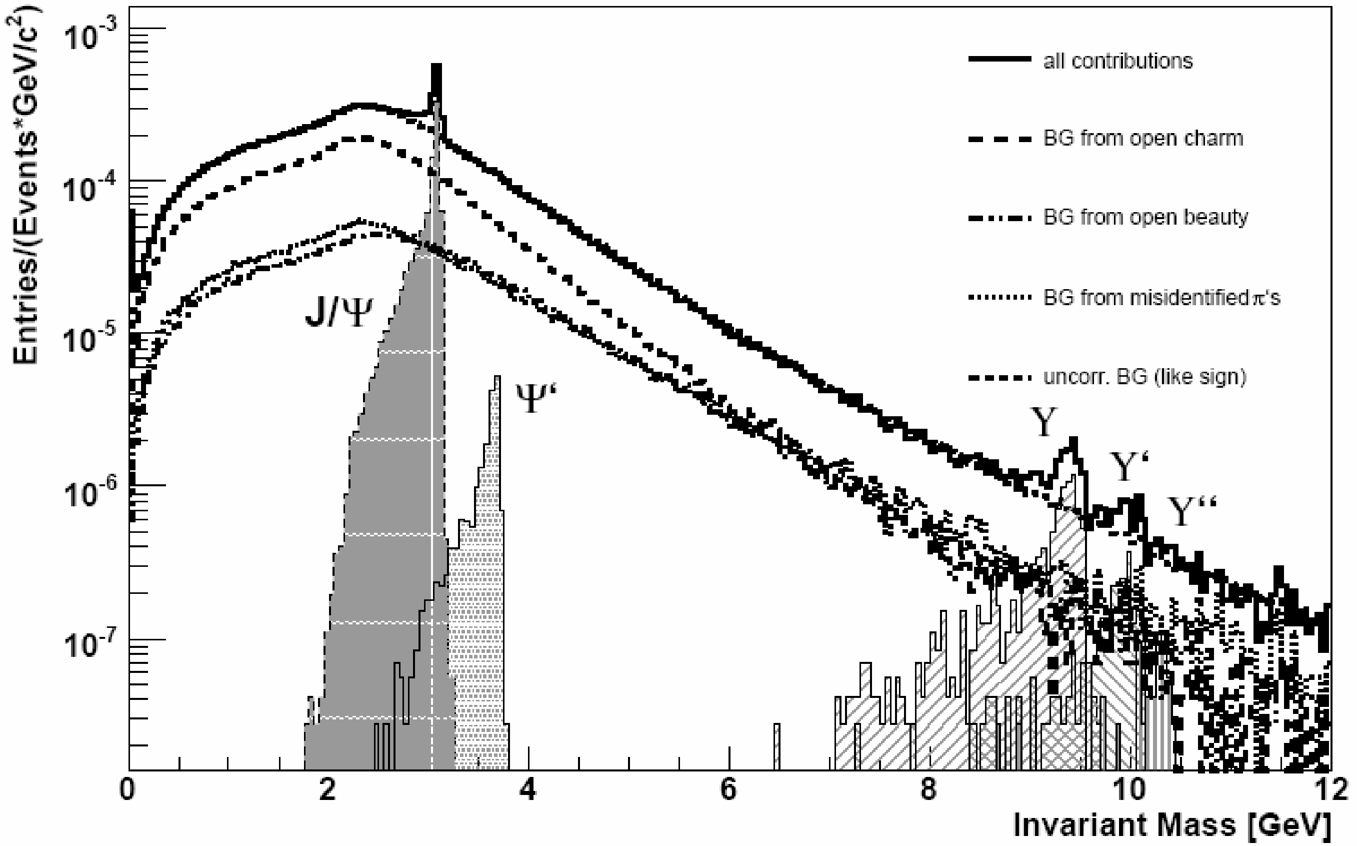
$$R_{D/h}(p_t) = R_{AA}^{D}(p_t) \big/ R_{AA}^{h}(p_t)$$



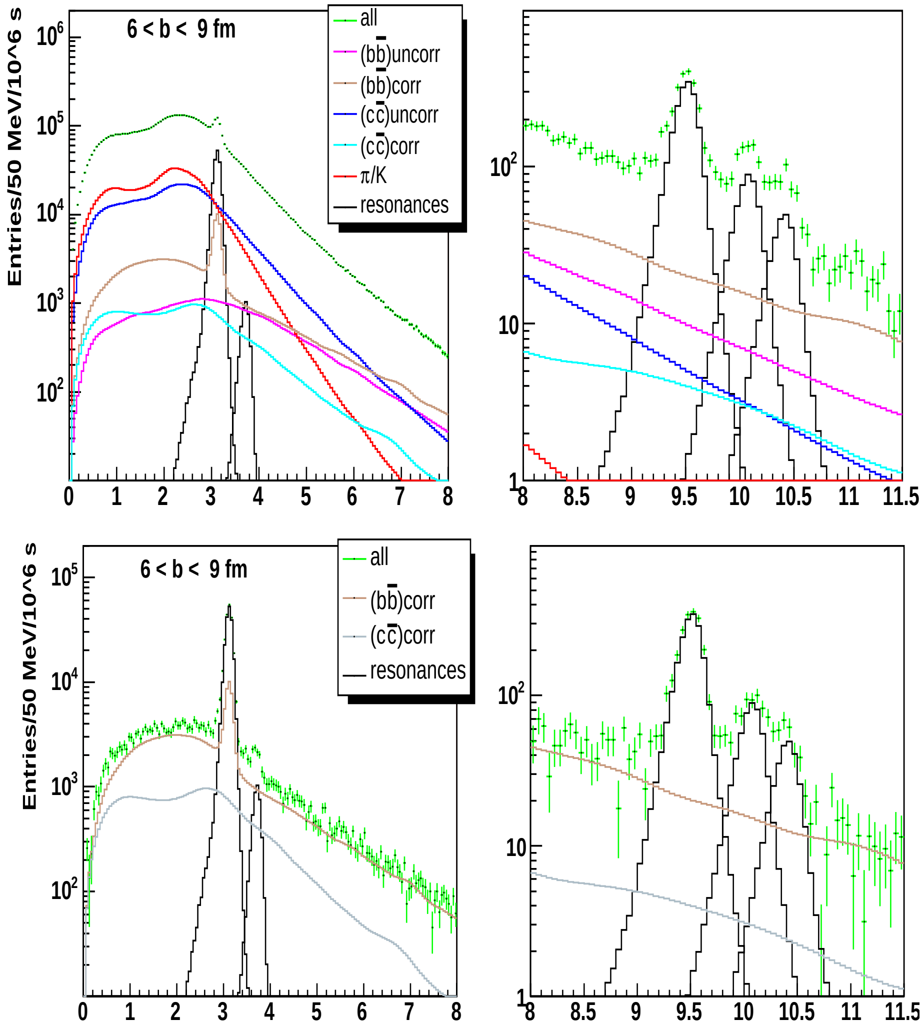
1 year at nominal luminosity
(10^7 central Pb-Pb events, 10^9 pp events)

Quarkonia→e^+e^-

State	$S\,(\times 10^3)$	$B\,(\times 10^3)$	S/B	$S/\sqrt{S+B}$
J/ψ	110.7	92.1	1.2	245
Υ	0.9	0.8	1.1	21
Υ'	0.25	0.7	0.35	8



Quarkonia → $\mu^+\mu^-$ (in PbPb)



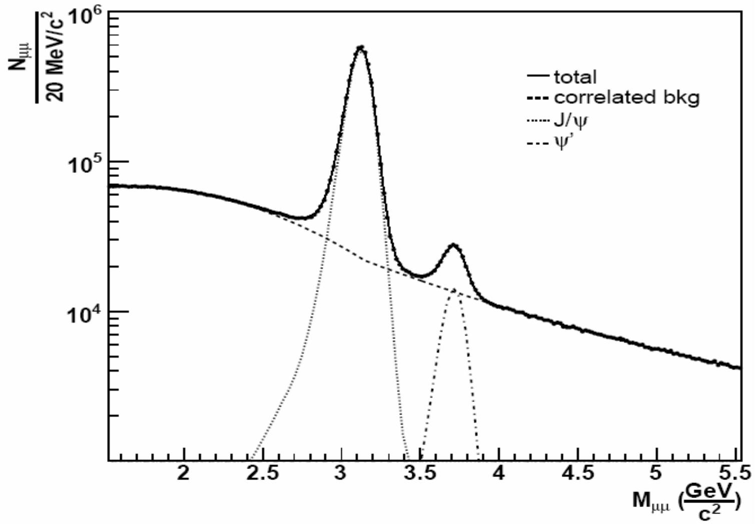
PbPb cent, 0 fm<b<3 fm

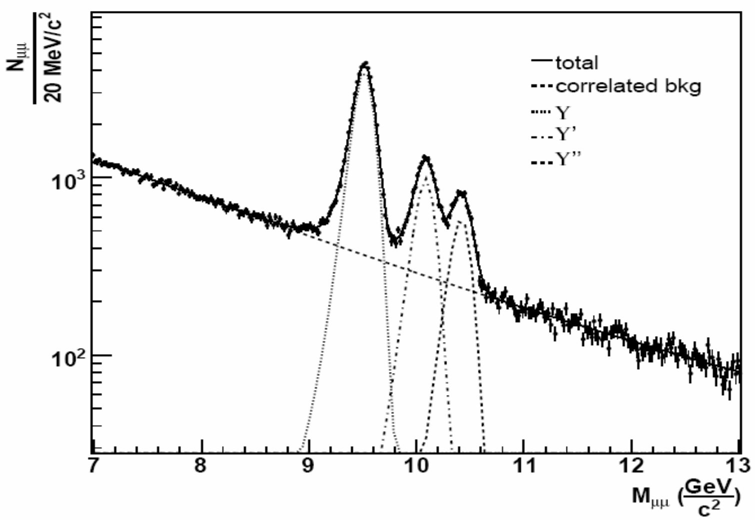
State	S[10^3]	B[10^3]	S/B	S/(S+B)$^{1/2}$
J/Ψ	130	680	0.20	150
Ψ'	3.7	300	0.01	6.7
ϒ(1S)	1.3	0.8	1.7	29
ϒ(2S)	0.35	0.54	0.65	12
ϒ(3S)	0.20	0.42	0.48	8.1

Yields for baseline

- ϒ(1S) & ϒ(2S) : 0-8 GeV/c
- J/Ψ high statistics: 0-20 GeV/c
- Ψ' poor significance
- ϒ'' ok, but 2-3 run will be needed.

Quarkonia → $\mu^+\mu^-$ (in pp at 14 TeV)





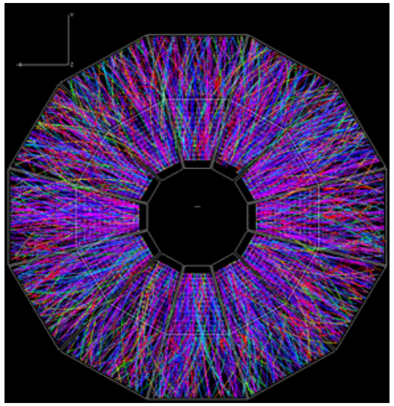
state	$B(\times 10^3)$	$S(\times 10^3)$	S/B	$S/\sqrt{S+B}$
J/ψ	370	4670	12.6	2081
ψ'	220	122	0.55	209
Υ	7.7	44.7	5.8	195
Υ'	6.1	11.4	1.9	86
Υ''	5.4	6.9	1.3	62

Highlights on physics topics -3

Jet physics

Jet studies with Heavy Ions at RHIC

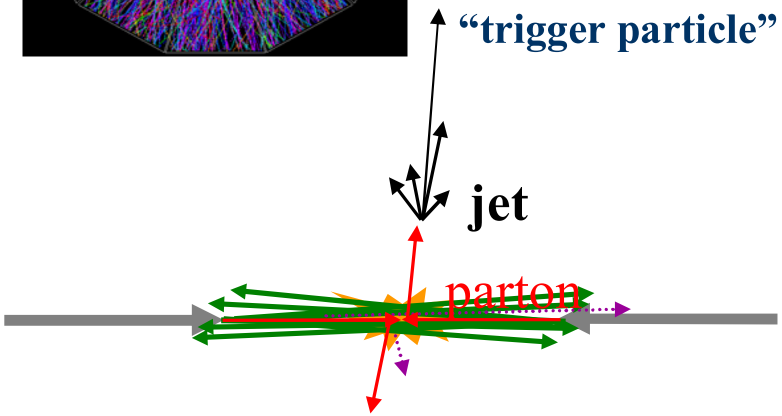
STAR Au+Au
$\sqrt{s_{NN}}$ = 200 GeV



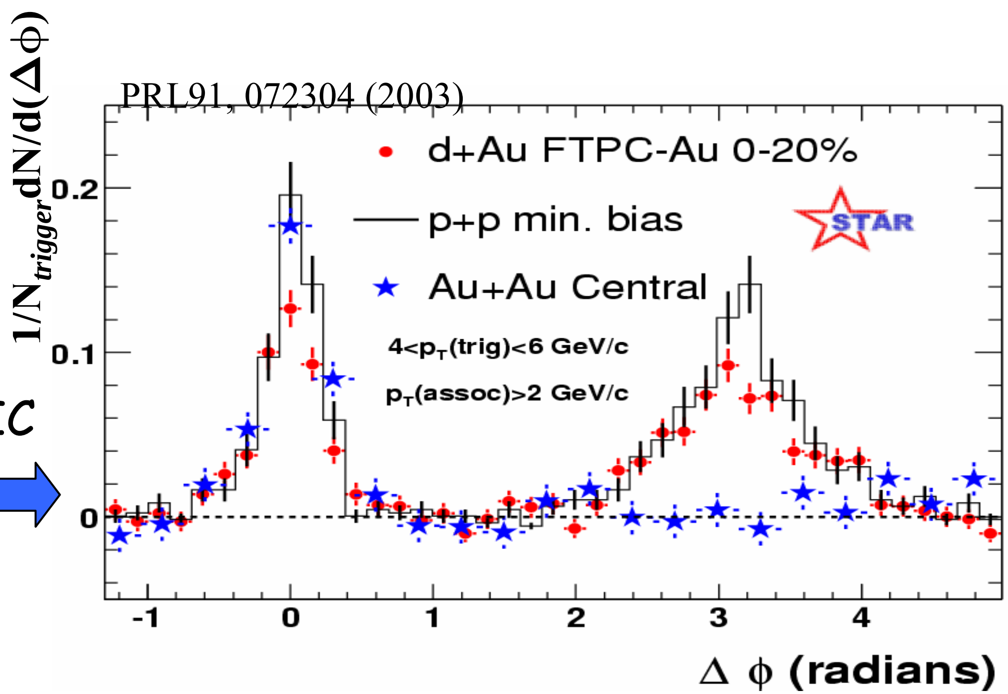
Standard jet reconstruction algorithms in nucleus-nucleus collisions **at RHIC fail** due to:

- **large energy from the underlying event** (125 GeV in *R*<0.7)
- limited reach up to relatively low jet energies (< 30 GeV)
- multi-jet production restricted to mini-jet region (< 2 GeV)

→ RHIC experiments use leading particles as a probe.

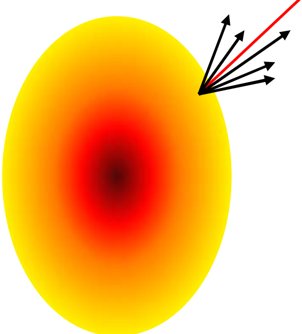


Evidence of parton energy loss at RHIC from the observed **suppression of back-to-back correlations** in Au-Au central collisions (and not in d-Au or p-p minbias)



Leading particle versus jet reconstruction

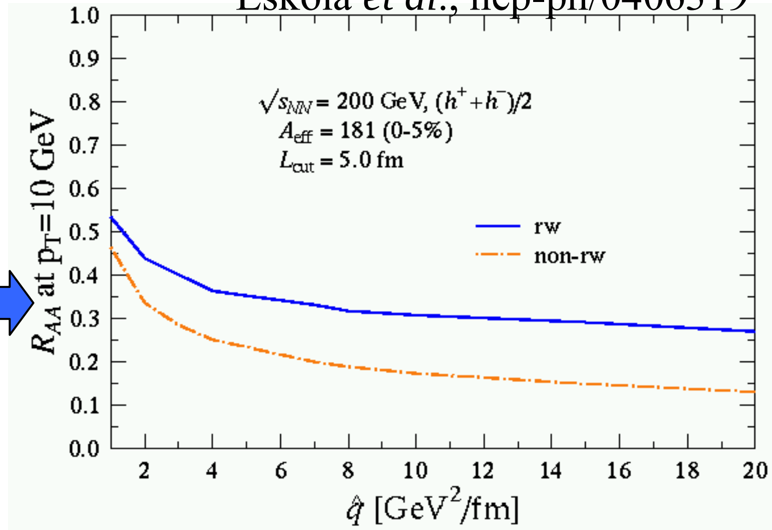
Leading Particle



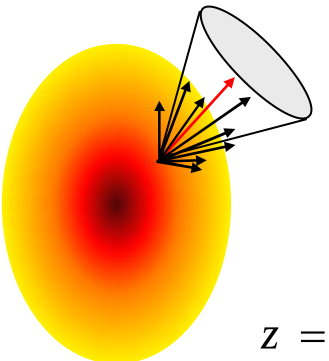
Leading particle is a fragile probe

- **Surface emission bias**
  - **Small sensitivity of R_{AA} to medium properties (at RHIC, but also at LHC)**
- For increasing in medium path length *L*, the momentum of the leading particle is less and less correlated with the original parton 4-momentum.

Eskola *et al.*, hep-ph/0406319



Reconstructed Jet



So, ideally only the **full jet reconstruction** allows to measure the original parton 4-momentum and the jet structure.

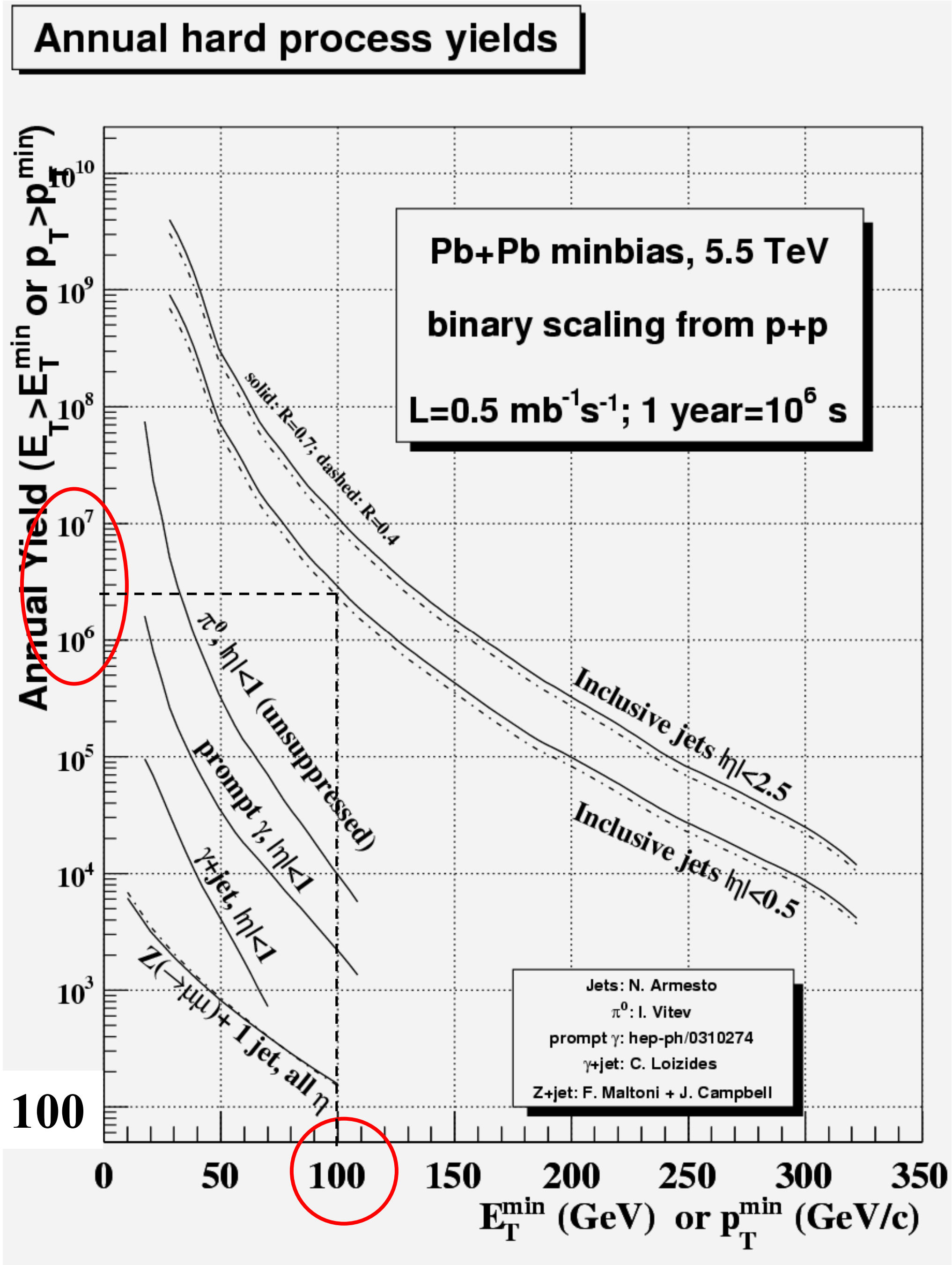
Study the properties of the QCD dense medium through **modifications of the jet structure** due to the parton energy losses (**jet quenching**):

$$z = \frac{p_T}{E_T^{jet}}$$

- **Decrease of particles with high z, increase of particles with low z**
- **Broadening of the momentum distribution perpendicular to jet axis**

Jet rates at the LHC

- **Copious production**!! Several jets per central PbPb collisions for E_T > 20 GeV
- Huge jet statistics for E_T~100 GeV
- Multi-jet production per event extends to ~ 20 GeV



Jet energy domain

2 GeV — 20 GeV — 100 GeV — 200 GeV

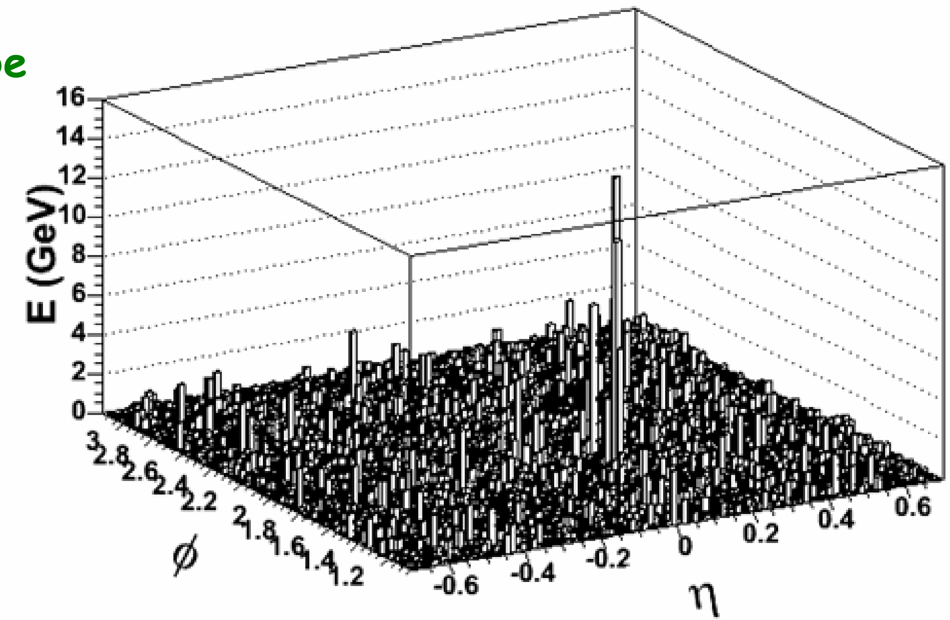
Mini-Jets 100/event — 1/event — 100k/month

No jet reconstruction, but only correlation studies (as at RHIC)
Limit is given by underlying event

Reconstructed Jets event-by-event well distinguishable objects

Full reconstruction of hadronic jets, even with the huge background energy from the underlying event, starts to be possible for jets with E> 50 GeV

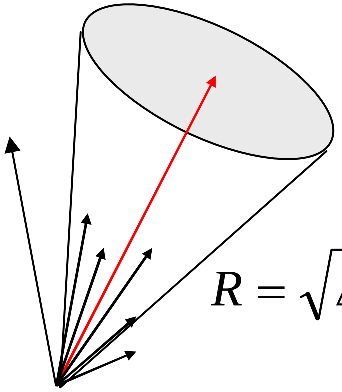
Example :
100 GeV jet +
underlying event



ALICE detectors for jet identification

- **Measurement of Jet Energy**
  - In the present configuration ALICE measures only charged particles with its Central Tracking Detectors
    (and electromagnetic energy in the PHOS)
  - The proposed Large EM Calorimeter (EMCal) would provide a significant performance improvement
    - E_T measured with reduced bias and improved resolution
    - Better definition of the fragmentation function: p_t/E_T
    - Larger p_t reach for the study of the fragmentation of the jet recoiling from a photon and photon-photon correlations
    - Excellent high p_t electrons identification for the study of heavy quark jets
    - Improved high E_T jet trigger
- **Measurement of Jet Structure** is very important
  - Requires good momentum analysis from ~ 1 GeV/c to ~ 100 GeV/c
  - ALICE excels in this domain
- pp and pA measurements essential as reference!

Jet reconstruction in ALICE



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

In **pp-collisions**

jets: excess of transverse energy within a typical cone of R = 1

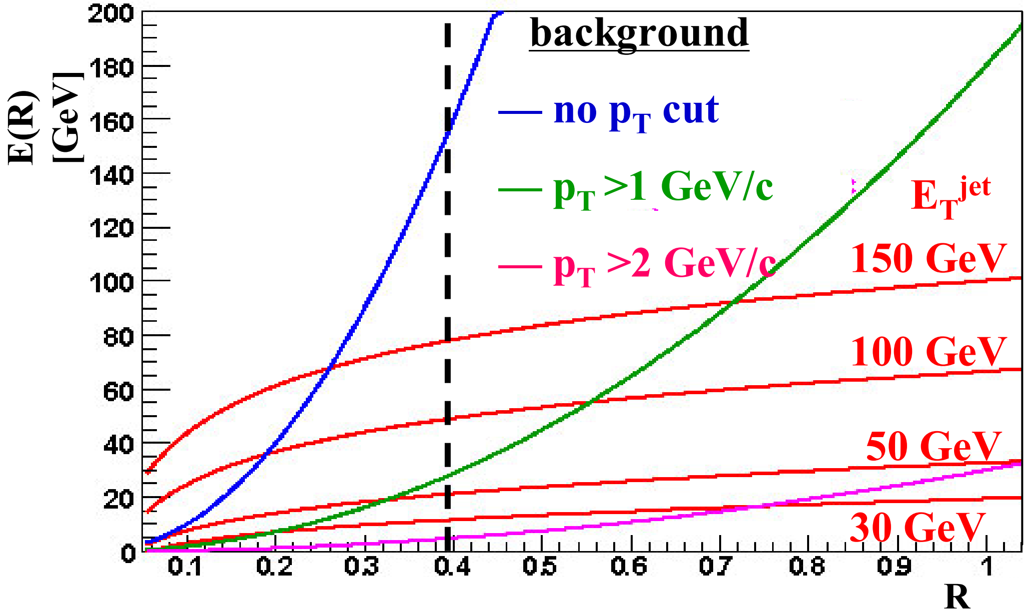
Main limitations in **heavy-ion collisions**:

- **Background energy (up to 2 TeV in a cone-size R=1)**
- **Background energy fluctuations**

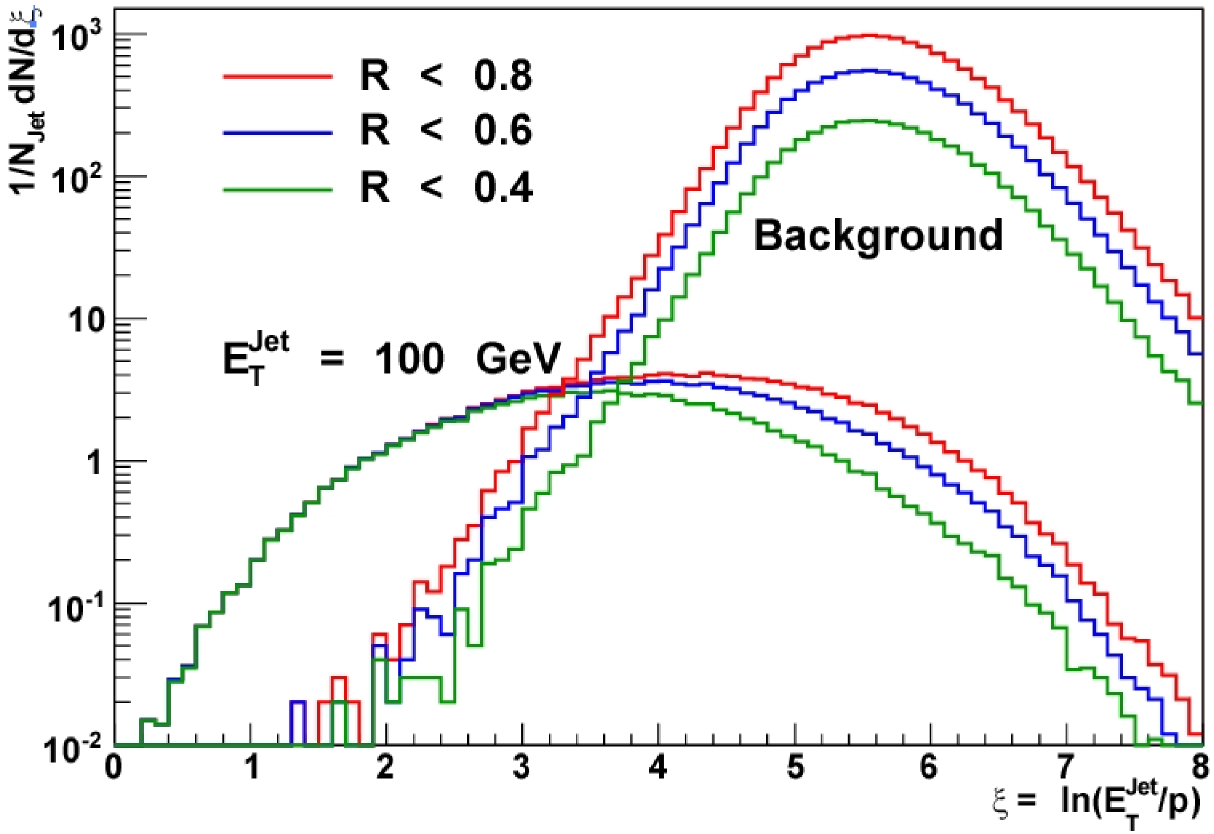
Background energy in a cone of size *R* is ~*R*^{2} (and background fluctuations ~*R*).

They can be reduced by:

- **reducing the cone size** (**R = 0.3-0.4**)
- and with transverse momentum cut (p_T = 1-2 GeV/c)



Background for jet structure observables: the hump-back plateau

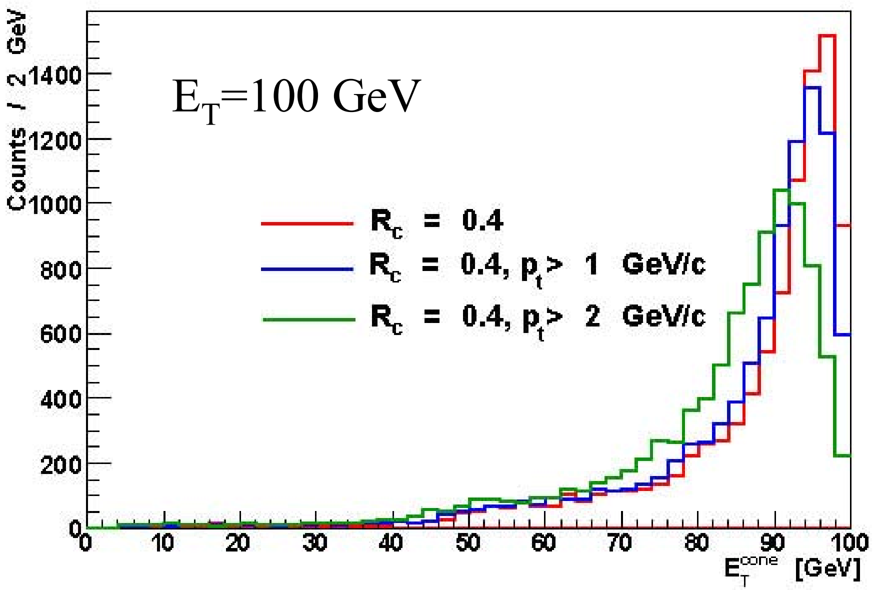


S/B > 0.1 for $\xi < 4$ leading particle remnants $p_t > 1.8$ GeV

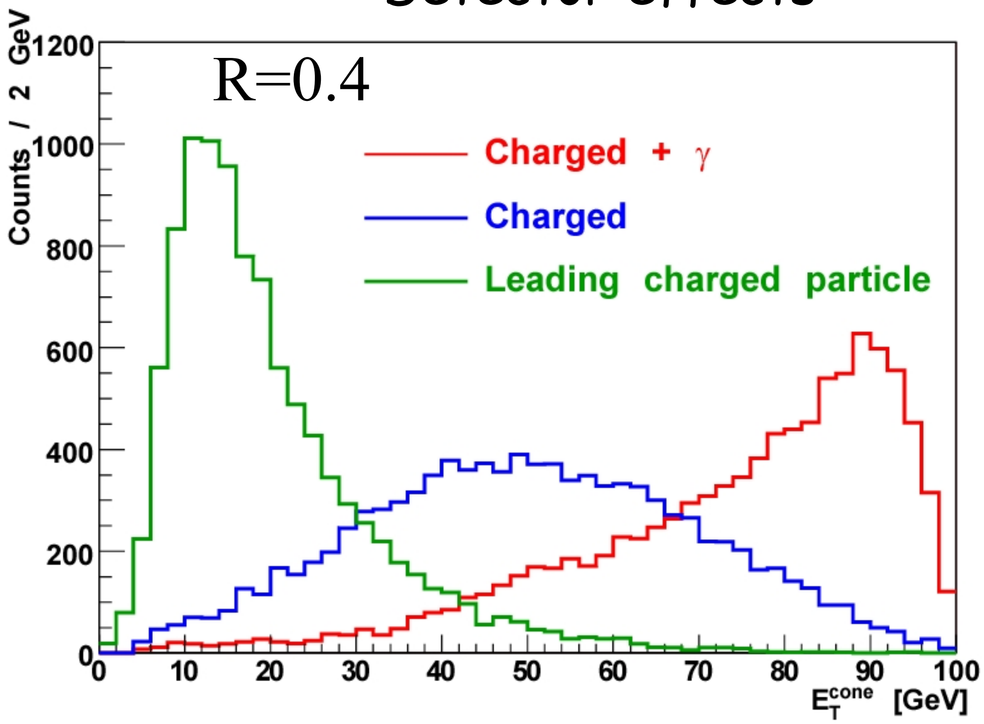
S/B ~ 10^{-2} for $4 < \xi < 5$ particles from medium-induced gluon radiation

Intrinsic jet reconstruction performance

Out-of-cone fluctuations



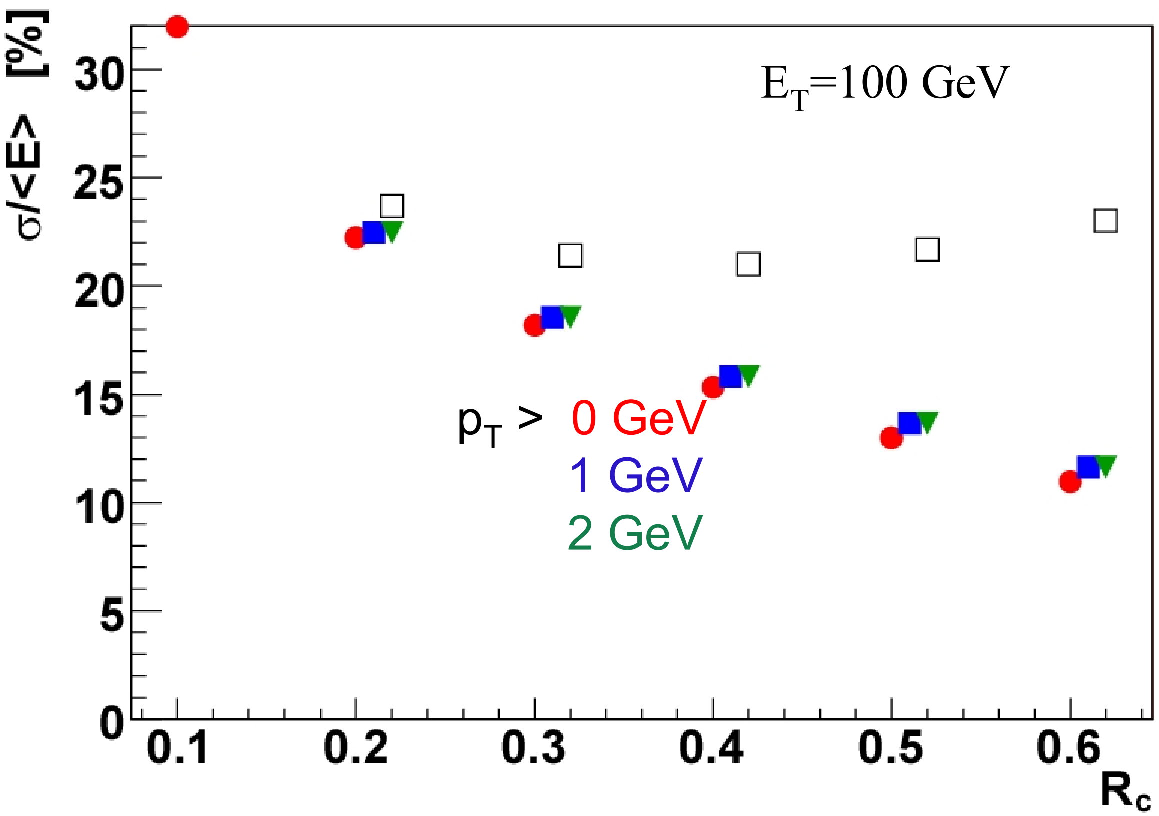
Detector effects



The limited cone-size and p_t cuts (introduced to reduce background energy) lead to a low-energy tail in the spectra of reconstructed energy.
This tail is enhanced if detector effects (incomplete or no calorimetry) are included

Assuming an ideal detector and applying a p_t-cut of 2 GeV/c we expect, for a jet with E_T=100 GeV a reconstructed cone energy of 88 GeV with gaussian fluctuations of 10%

Energy resolution (for ideal calorimetry)



Background fluctuations added to signal fluctuations for the case p_t>1 GeV/c

Cone-size 0.3 < R< 0.5 : optimal limiting resolution $\Delta E_T/E_T$ ~22 %

Photon-tagged jets

Dominant processes:

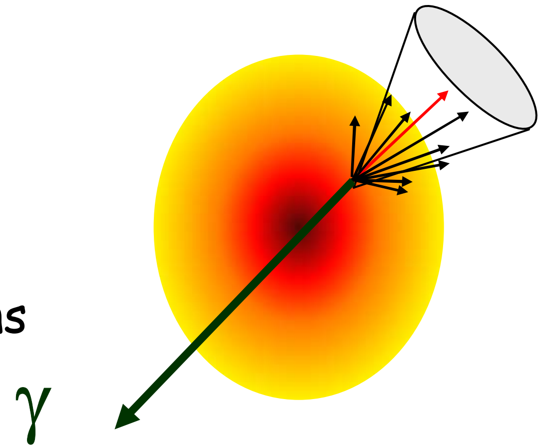
$g + q \rightarrow \gamma + q$ (Compton)

$q + \bar{q} \rightarrow \gamma + g$ (Annihilation)

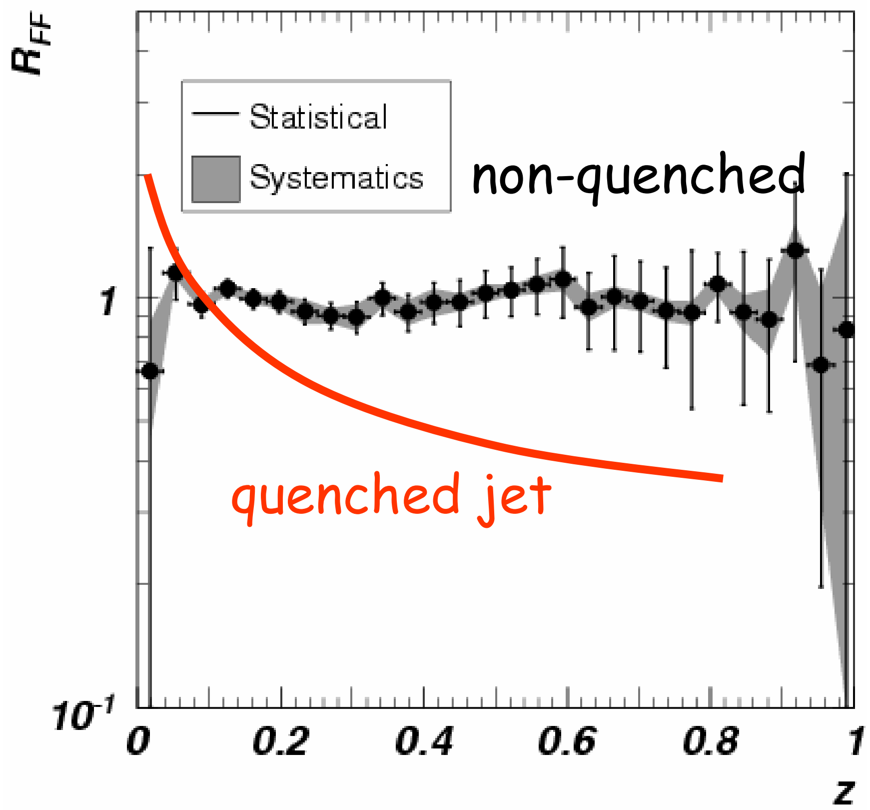
$p_T > 10$ GeV/c

γ-jet correlation

- $E_\gamma = E_{jet}$
- Opposite directions



- γ energy provides independent measurement of jet energy
- Drawback: low rate !!
- But... especially interesting in the intermediate range (tens of GeV) where jets are not identified
- Direct photons are not perturbed by the medium
- Parton in-medium-modification through the fragmentation function and study of the nuclear modification factor R_{FF}

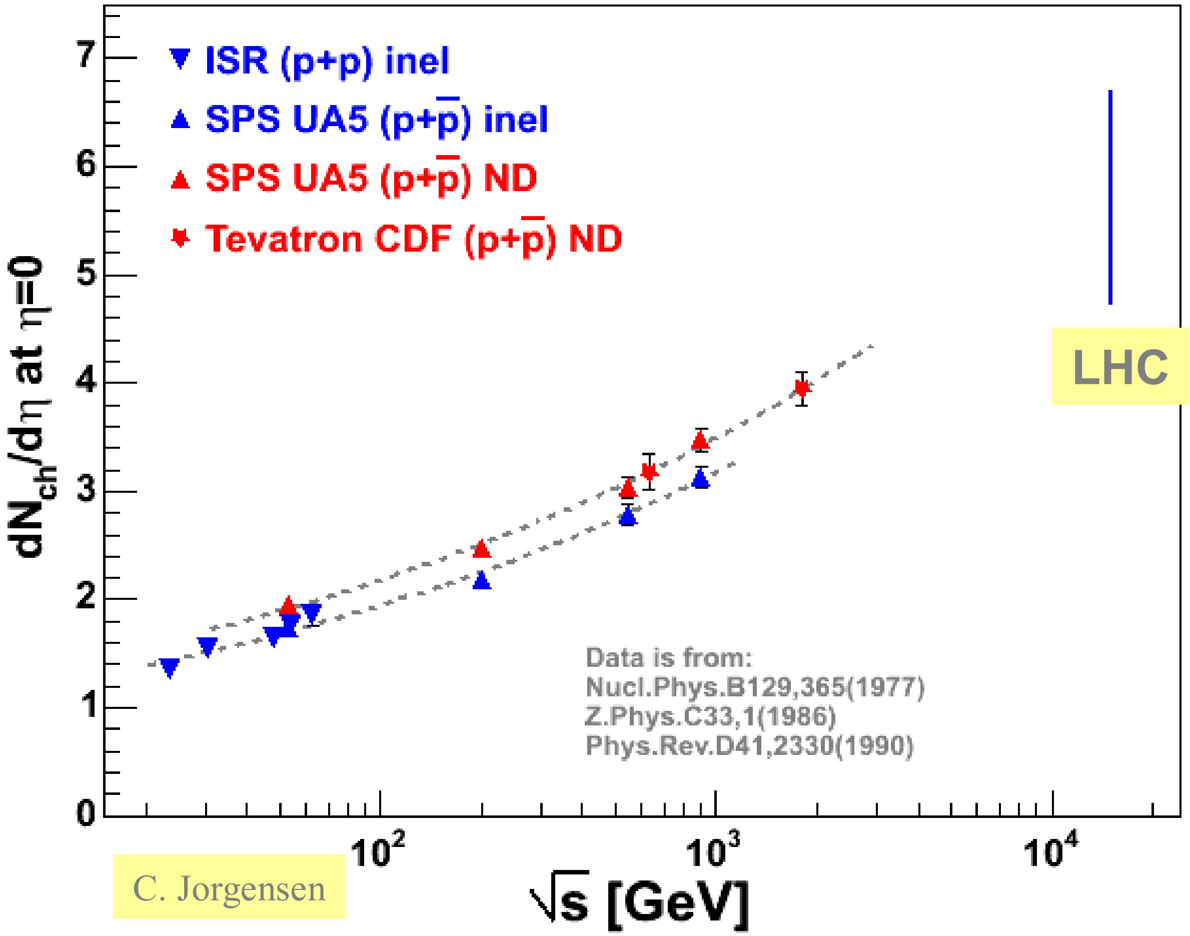


Summary

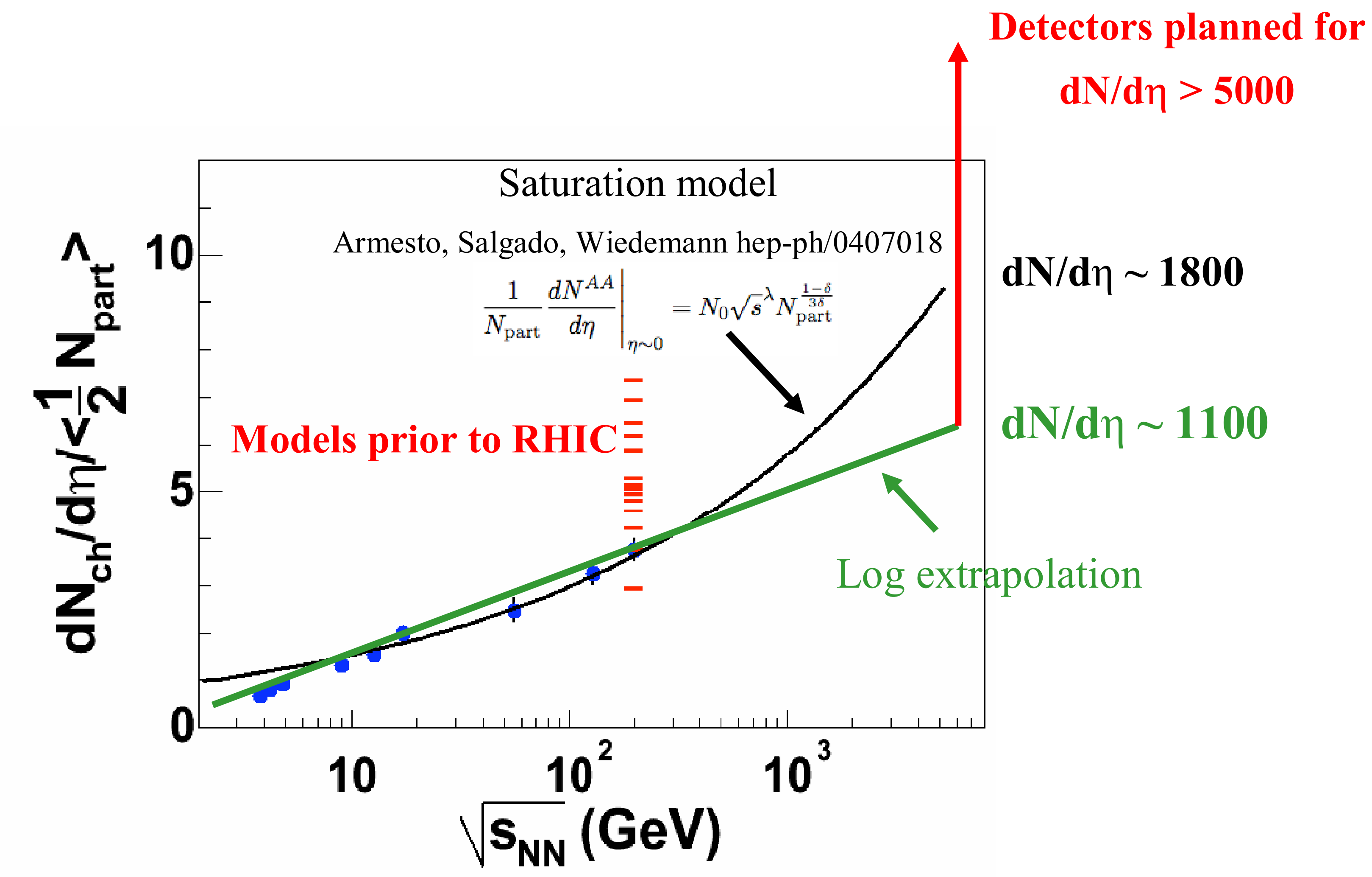
- ALICE is well suited to measure **global event properties** and **identified hadron spectra** on a wide momentum range (with very low p_T cut-off) in Pb-Pb and pp collisions.
- Robust and efficient tracking for particles with momentum in the range 0.1 – 100 GeV/c
- Unique particle identification capabilities, for stable particles up to 50 GeV/c, for unstable up to 20 GeV/c
- The nature of the bulk and the influence of hard processes on its properties will be studied via **chemical composition, collective expansion, momentum correlations** and **event-by-event fluctuations**
- **Charm and beauty production** will be studied in the p_T range 0-20 GeV/c and in the pseudo-rapidity ranges $|\eta|<0.9$ and $2.5<\eta<4.0$
- High statistics of **J/Ψ** is expected in the muon and electronic channel
- **Upsilon family** will be studied for the first time in AA collisions
- ALICE will **reconstruct jets** in heavy ion collisions
  → study the properties of the dense created medium
- ALICE will identify **prompt and thermal photons** → characterize initial stages of collision region (Y. Kharlov's talk)

BACKUP SLIDES

Expected multiplicities at the LHC in pp collisions



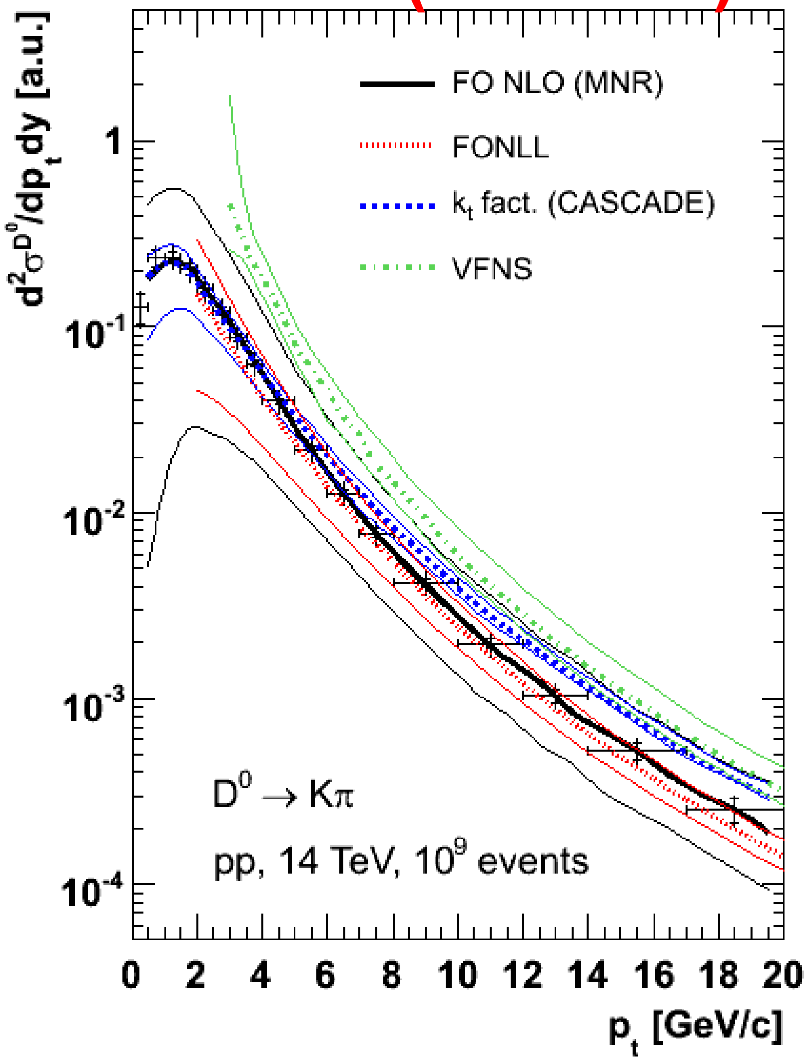
Expected multiplicities at the LHC in PbPb collisions



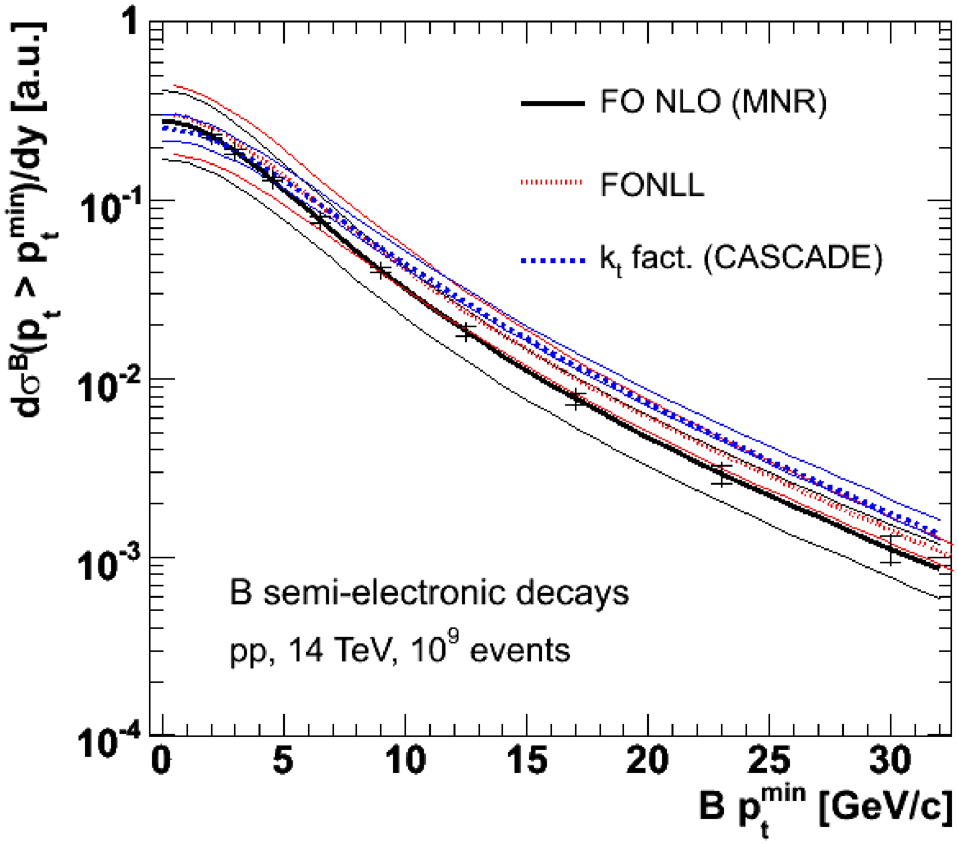
Comparison to pQCD predictions

pp, $\sqrt{s}$ = 14 TeV

charm ($D^0 \rightarrow K\pi$)



beauty ($B \rightarrow e+X$)



1 year at nominal luminosity
(10^9 pp events)

Machine time scale (as envisaged today)

- **T0** (= 1st of July 2007 as of today)
- One month to get the machine ready for beams (**T0 + 1 month**)
- Three months to commission the machine with beams (**T0 + 4 months**)
  => possibility for ALICE to collect the first pp data sample for first paper!
- One month of rather stable operations, interleaved with machine development with 43 and 156 bunches, with the possibility of collisions for physics during nights (~ 20 shifts of 10 hours each L ~ $10^{30} cm^{-2} s^{-1}$) (**T0 + 5 months**)
  => possibility for ALICE to collect the first large pp data sample!
- Perhaps first Pb-Pb collisions.
- Shutdown (**T0 + 8 to 9 months**): today machine people talk about 3 to 4 months. It will depend on requirements by experiments.
  If T0 = 1st of July, start of shutdown will coincide with the Christmas holidays.