Highlights of the ALICE Physics Program at the LHC

International School on Quark-Gluon Plasma and Heavy Ion Collisions: past, present, future

4th edition – Torino, Dec. 8-14, 2008

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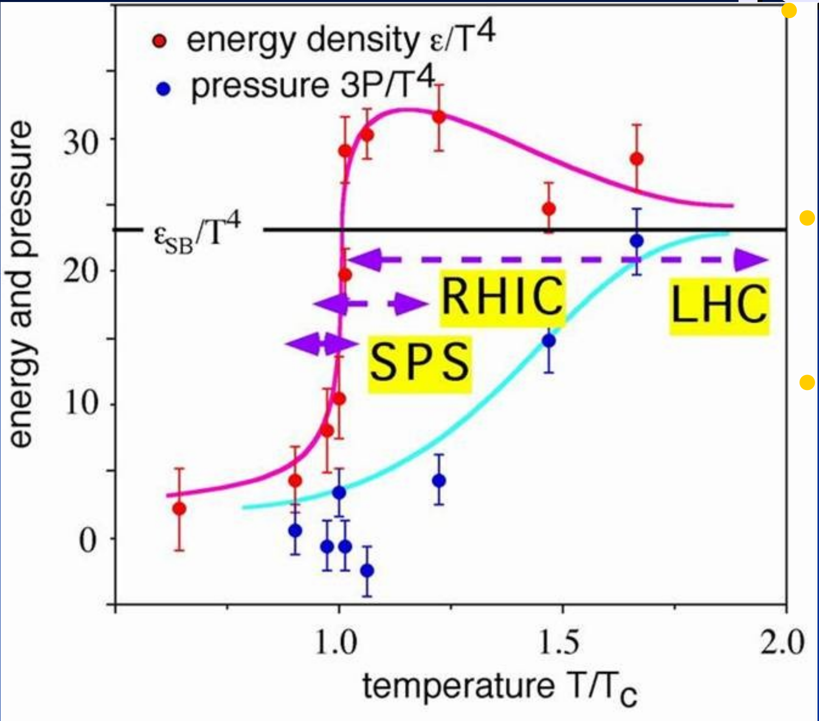
for the ALICE Collaboration

Topics

- The ALICE experiment at LHC
- Hard probes
  - see also D'Enterria, Drapier, Mocsy, Salgado
- Soft probes
  - see also Becattini, Sorensen, Stock, Romatschke
- pp physics: "first physics", reference for Pb-Pb

QGP @ LHC: hotter, larger, longer



Parameter		SPS	RHIC	LHC
$\sqrt{s_{NN}}$	[GeV]	17	200	5500
dN_{gluons}/dy		$\simeq 450$	$\simeq 1200$	$\simeq 5000$
dN_{ch}/dy		400	650	$\simeq 3000$
Initial temperature	[MeV]	200	350	> 600
Energy density	[GeV/fm^3]	3	25	120
Freeze-out volume	[fm^3]	few 10^3	few 10^4	few 10^5
Life-time	[fm/c]	< 2	2-4	> 10

- To cover the high temperature region of the QCD phase diagram, one has to increase √s of the collision
- But the energy density ε increases rather slowly with √s
- Keeping a fixed τ_0 (formation time) one has:

$$\varepsilon\ (\tau=1\ \text{fm}/c) \sim dN/dy \sim \ln(\sqrt{s})$$

(actually, formation times are expected to decrease with √s)

... and temperature increases slowly when increasing ε:

$$\varepsilon \propto T^4 \text{ (Stefan-Boltzmann)}$$

Significant increase in T, dimension and lifetime of the QGP phase is anyway expected at the LHC!

New regimes at LHC energies

- Bjorken-x range down to $x<10^{-5}$ at LHC: access region of gluon saturation, expect significant nuclear gluon shadowing in PDF's
- Hard processes contribute significantly to the total A-A cross section: charm, beauty (both quarkonia & open flavor), jets will be available as strongly interacting hard probes
- Weakly interacting hard probes Z^0 and $W^{\pm}$ will become available
- QGP lifetime significantly larger than time needed for thermalisation of the system: collective features of the observed hadronic final state more directly related to the early stages, parton dynamics will dominate the fireball expansion

ALICE: a dedicated H.I. experiment

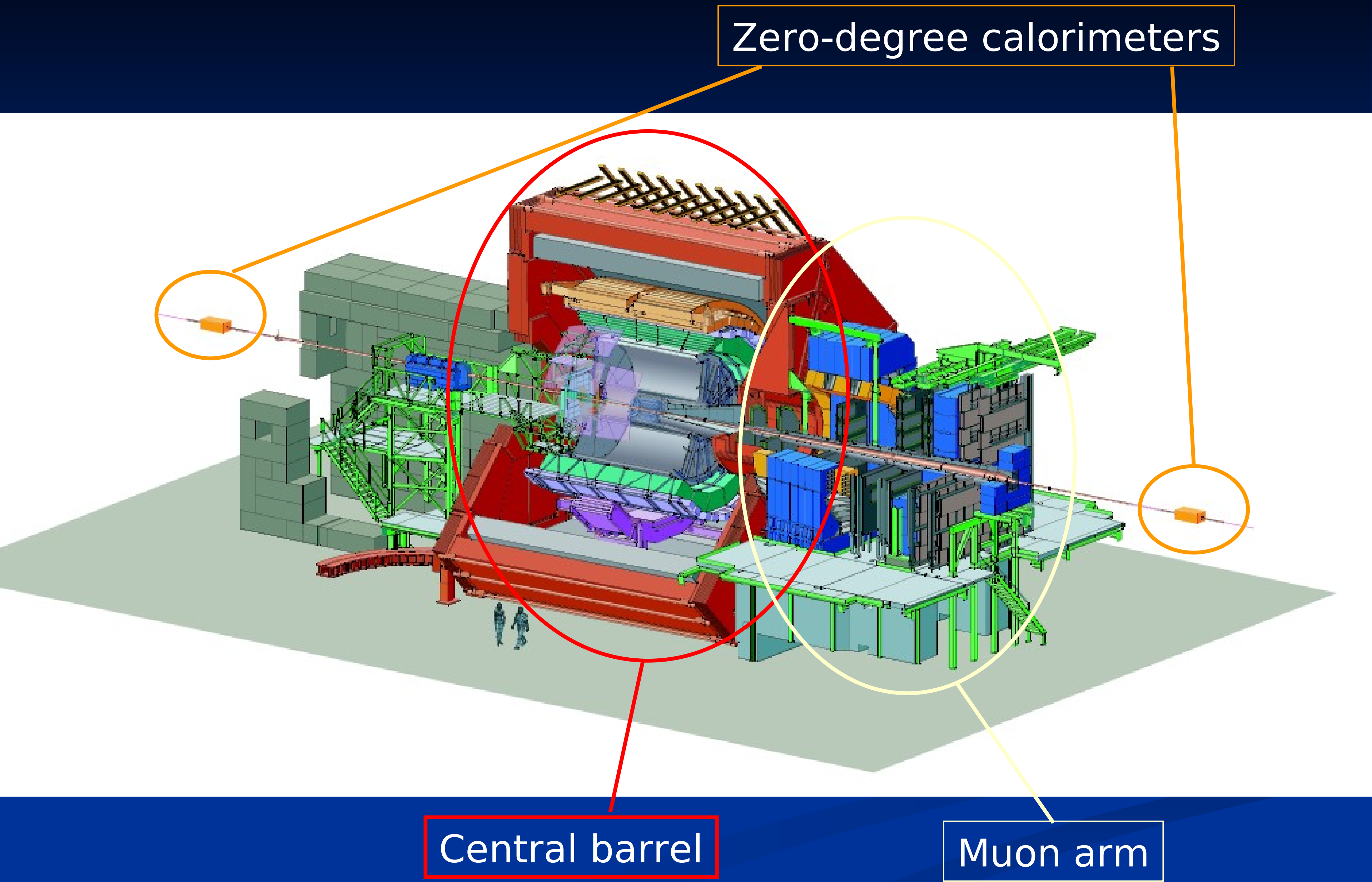
- General purpose (contrarily to SPS and, to a certain extent, to RHIC)
- In contrast to experiments mainly devoted to study (hard) p-p physics at the LHC, an experiment focussed on heavy-ion physics should have:

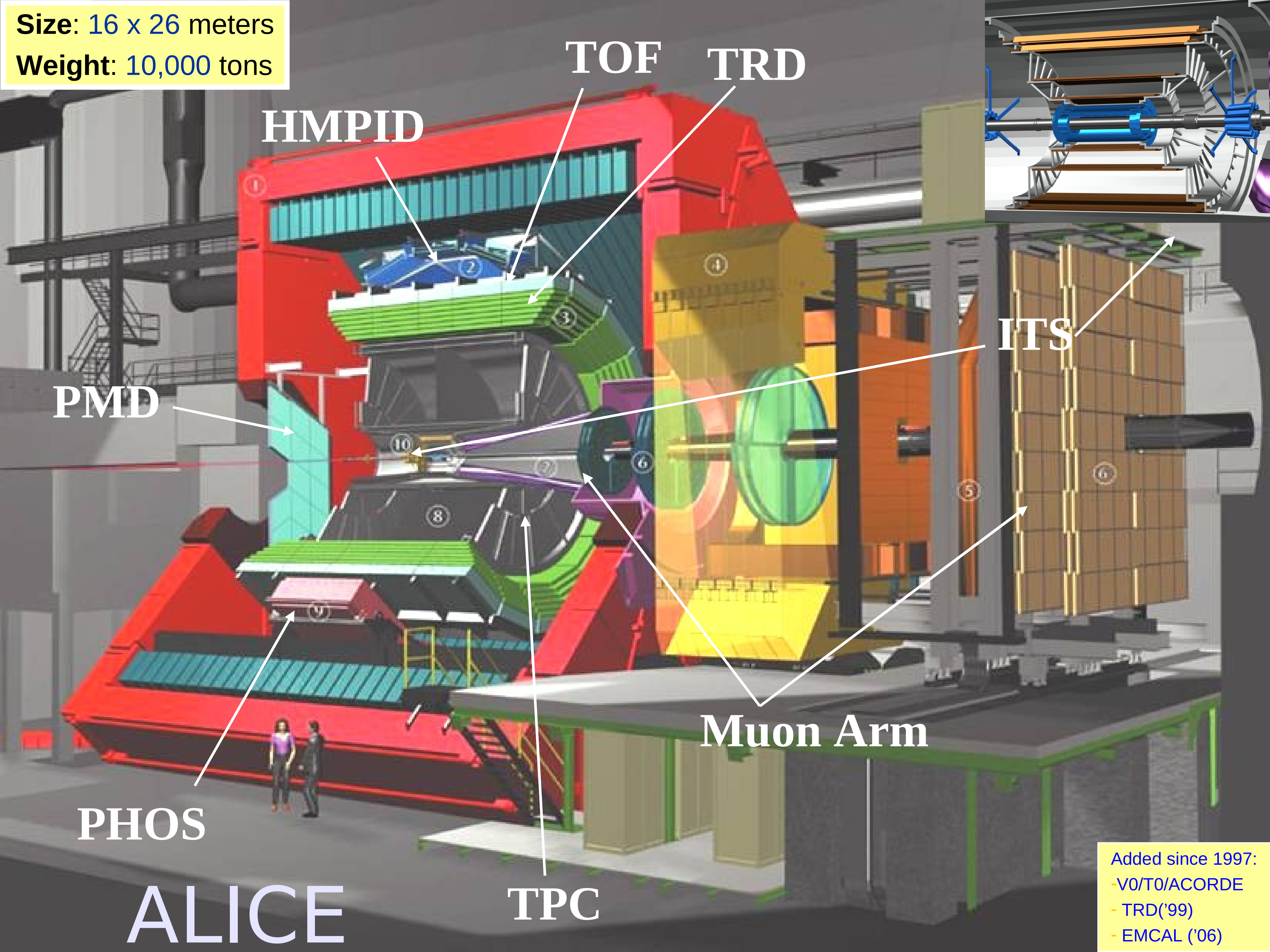
1) The capability of coping with the high multiplicity generated in H.I. collisions (2000 charged particles per unit rapidity)

- Not really necessary for selected hard probes such as $\Upsilon \rightarrow \mu\mu$, but important to access the bulk of particle production, i.e. to study soft observables (e.g. flow)
- Implies, in particular:
  - High granularity
  - Large bandwidth for Data Acquisition system

2) The possibility of pushing down as much as possible its p_T reach

Implies a not too high B field for momentum measurement
→ Conflicting requirement with accuracy for hard probes!


Zero-degree calorimeters
Central barrel
Muon arm



Size: 16 x 26 meters
Weight: 10,000 tons

ALICE

Added since 1997:
- V0/T0/ACORDE
- TRD('99)
- EMCAL ('06)

ALICE configuration at start-up

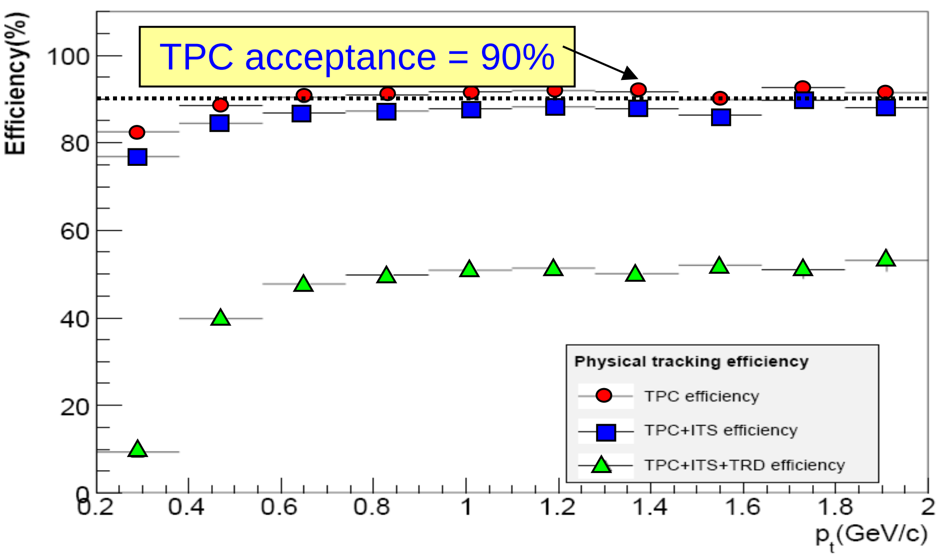
- Complete - fully installed & commissioned:
  - ITS, TPC, TOF, HMPID, MUONS, PMD, V0, T0, FMD, ZDC, ACORDE, TRIGGER, DAQ
- Partially completed:
  - TRD (20%) to be completed by 2009
  - PHOS (40%) to be completed by 2010
  - EMCAL (0%) to be completed by 2010/11
- At start-up full hadron and muon capabilities,
- Partial electron and photon capabilities

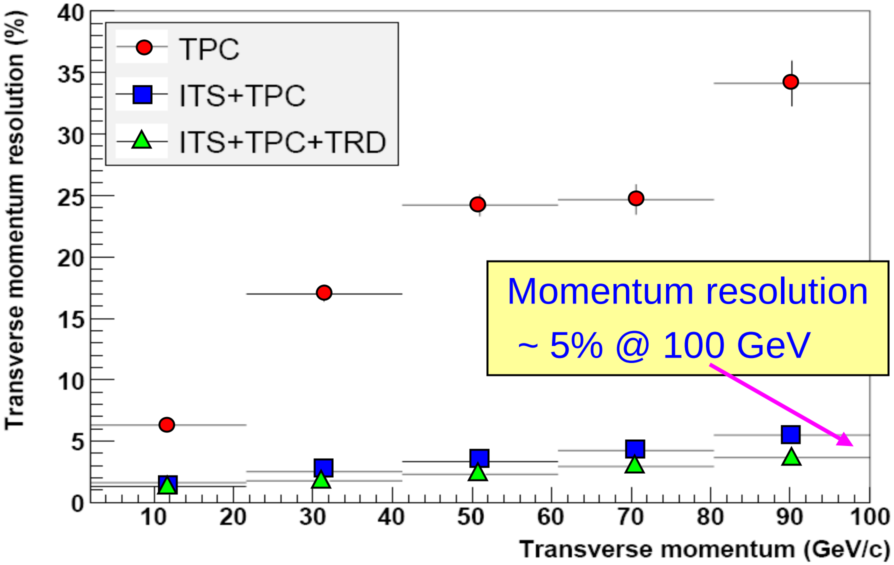
Alice tracking performance

Central barrel tracking: ITS + TPC + TRD

Robust, redundant tracking from < 100 MeV/c to > 100 GeV

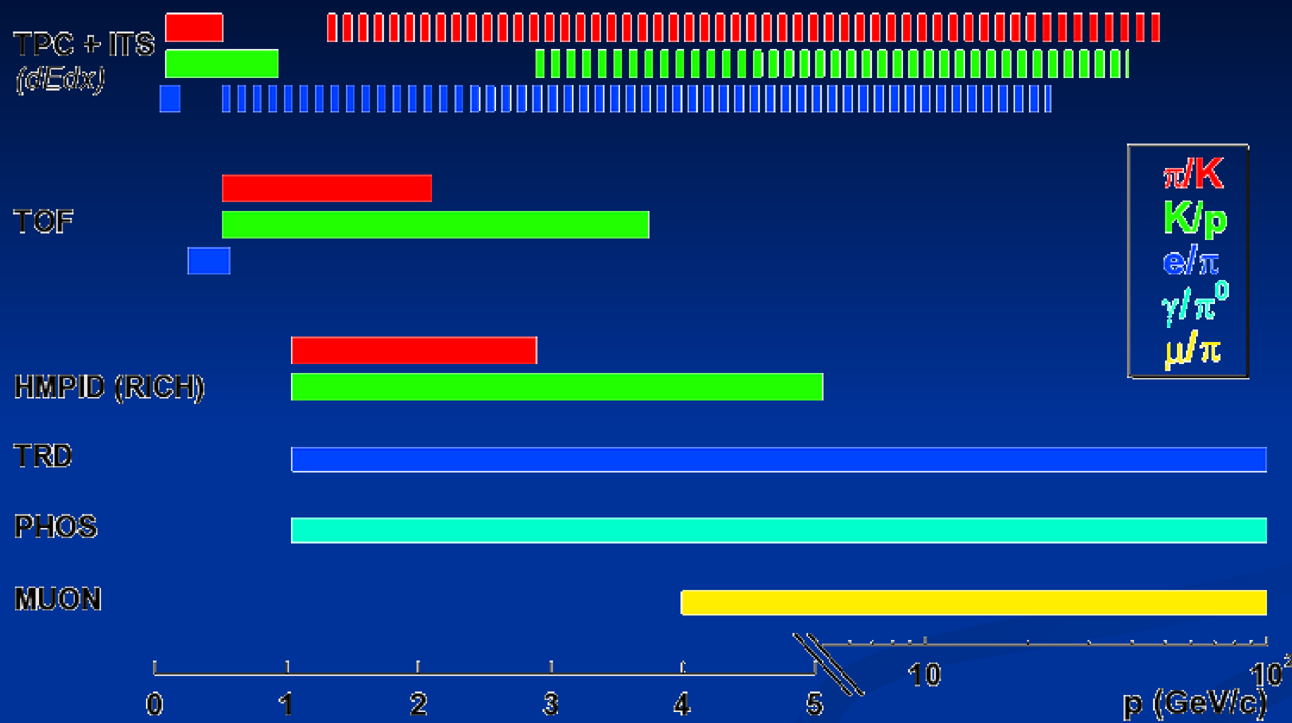
Very little dependence on dN_{ch}/dy up to $dN_{ch}/dy \approx 8000$





- $\delta p/p < 5\%$ at 100 GeV with careful control of systematics

Alice particle identification

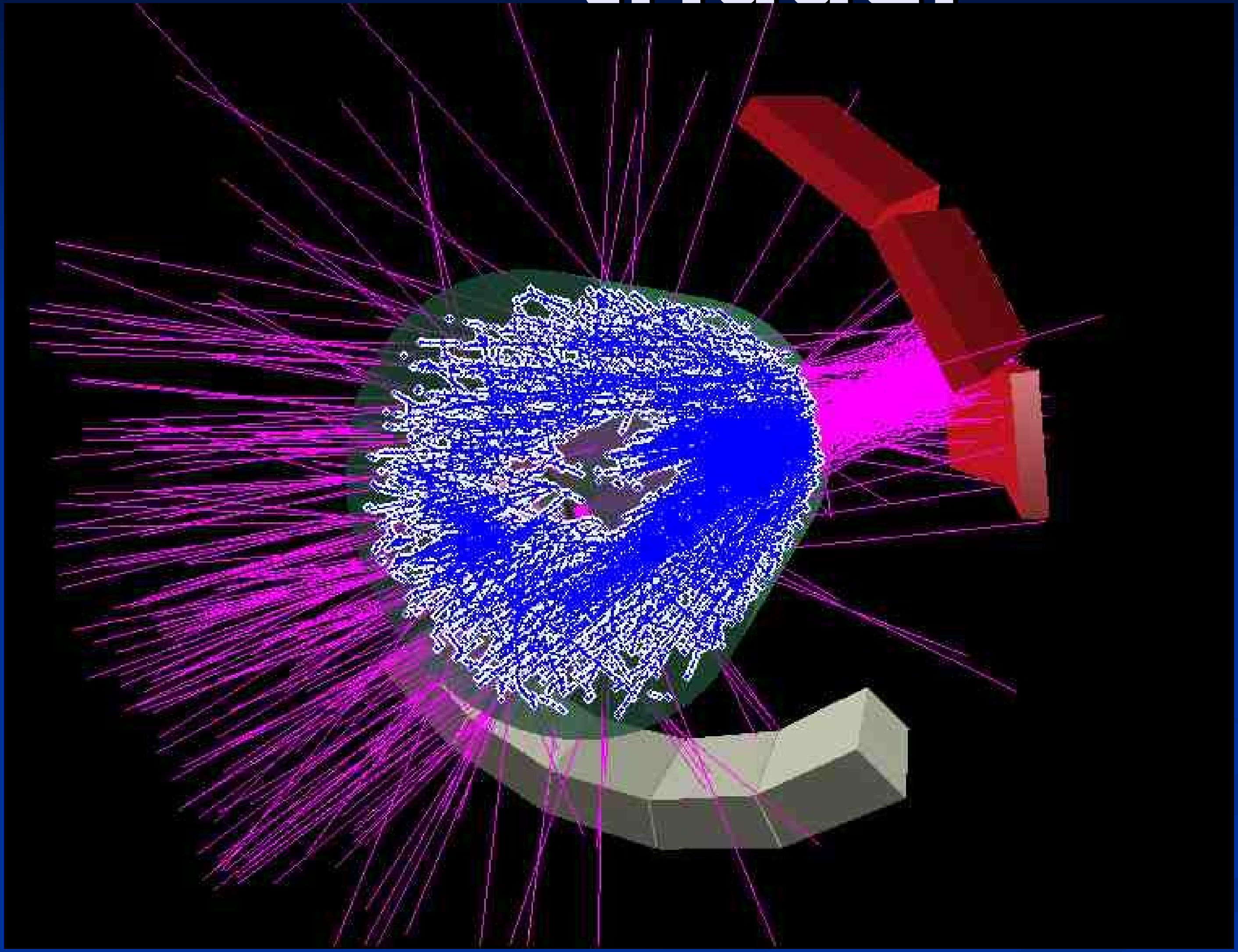


- ‘stable’ hadrons (π, K, p): 0.1<p<5 GeV/c; (π,p with ~ 80 % purity to ~ 60 GeV/c)
  → dE/dx in silicon (ITS) and gas (TPC) + time-of-flight (TOF) + Cherenkov (RICH)

- decay topologies (K^0, K^+, K^-, Λ, cascades, D)
  → K and Λ decays beyond 10 GeV/c

- leptons (e,μ), photons, π^0
  → electrons TRD: p > 1 GeV/c, muons: p > 5 GeV/c, π^0 in PHOS: 1<p<80 GeV/c

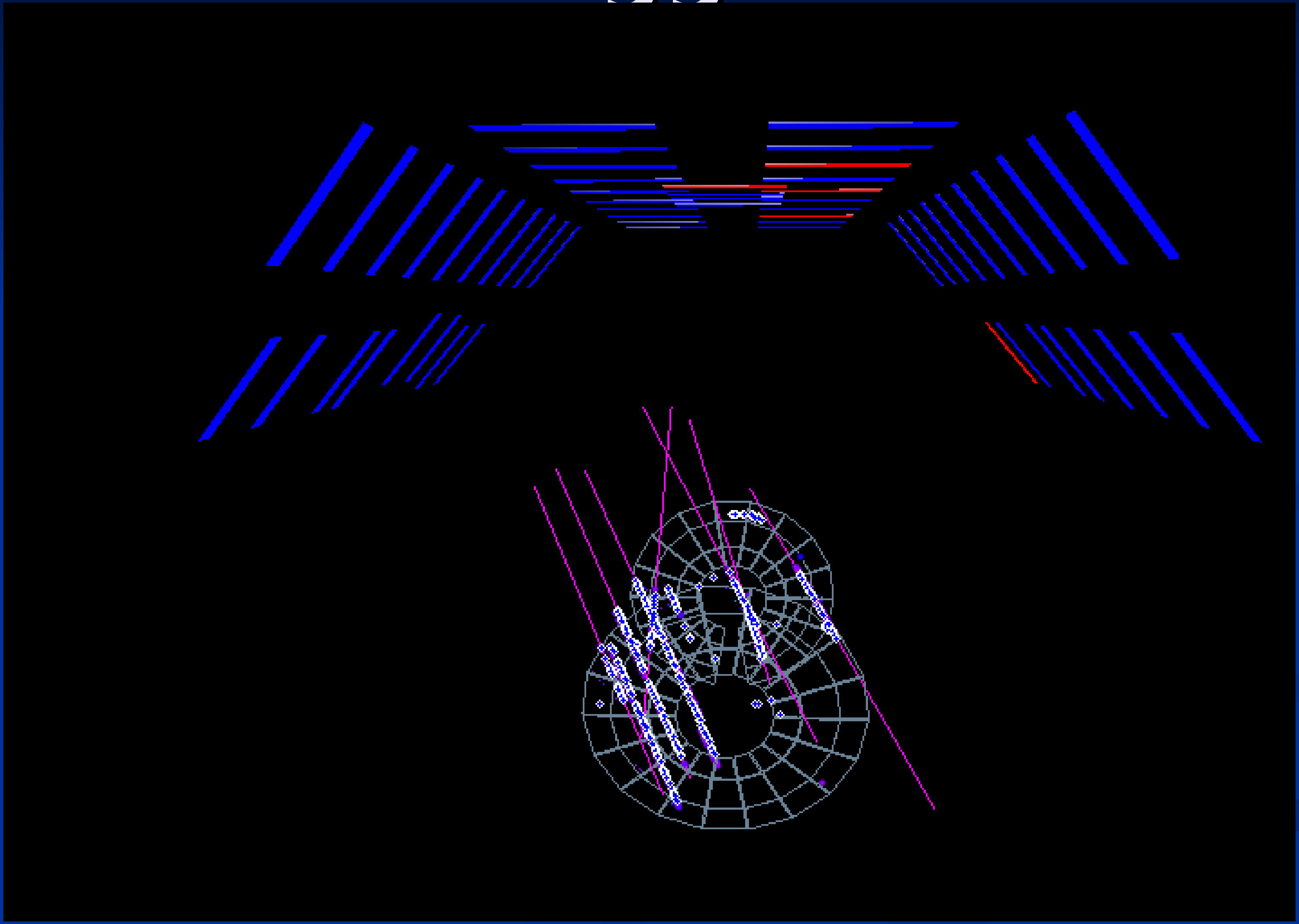
Cosmic event with SPD trigger



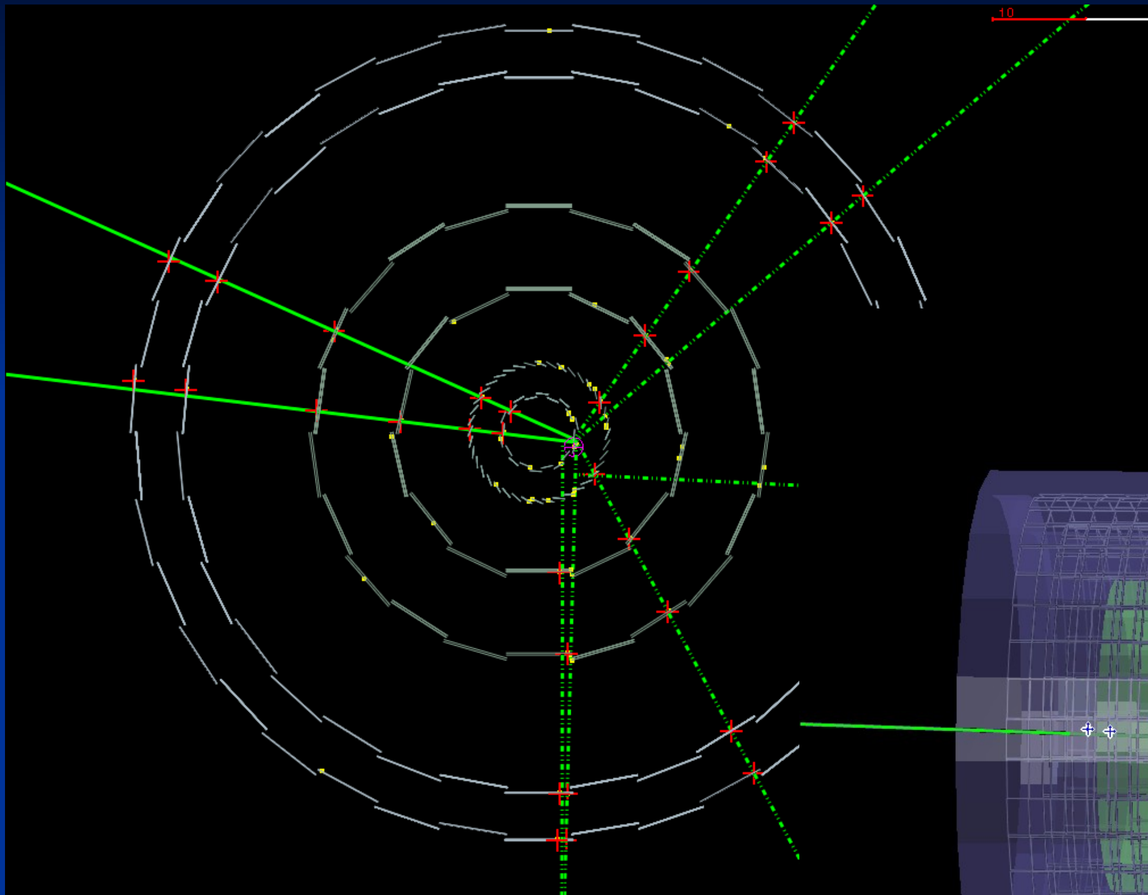
Probably a muon interaction in the magnet's iron

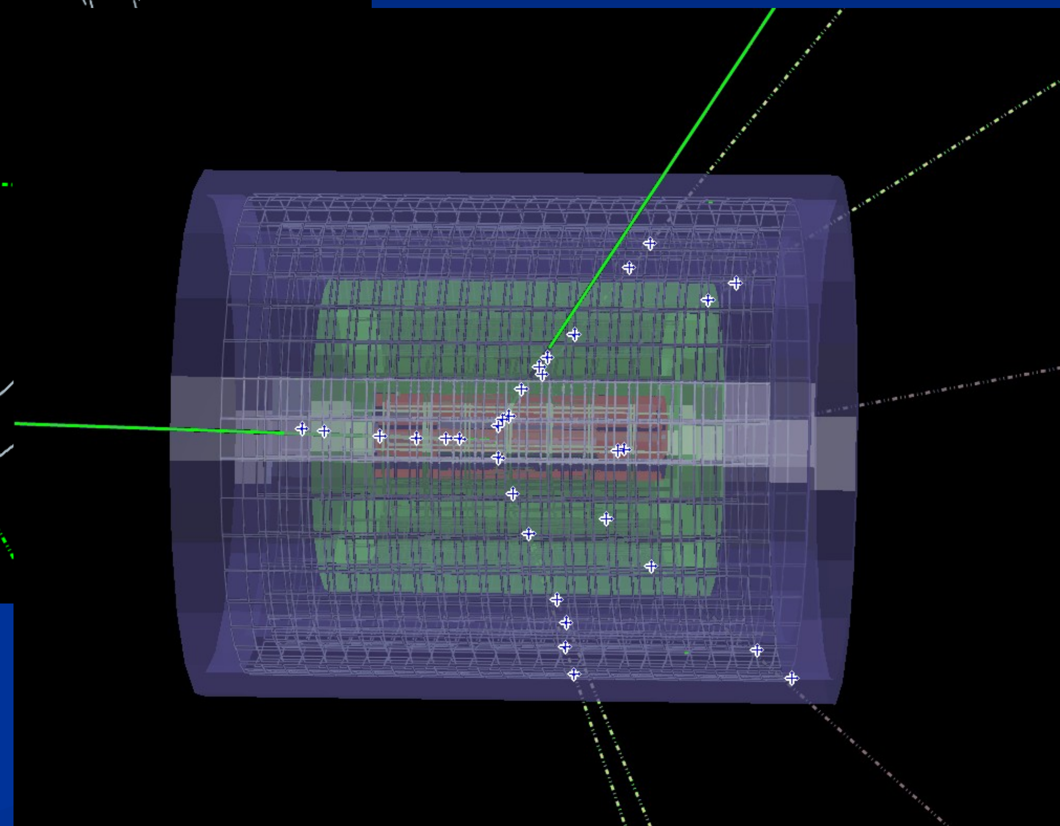
about 350 tracks reconstructed in TPC

Cosmic event with ACORDE trigger



p beam in ALICE





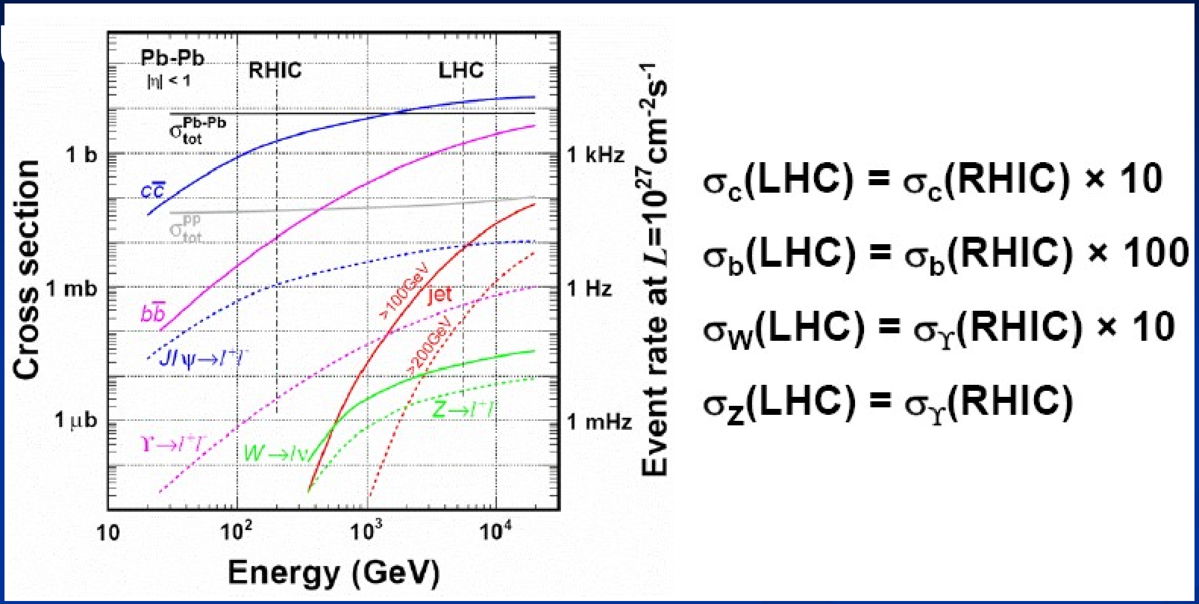
LHC pilot beam at 450 GeV:
p-Si collision in the SPD
(Sept. 12, 2008)

Hard probes

- open charm and beauty
- quarkonia
- jets

Charm and Beauty

- Large cross-sections for heavy quark produ

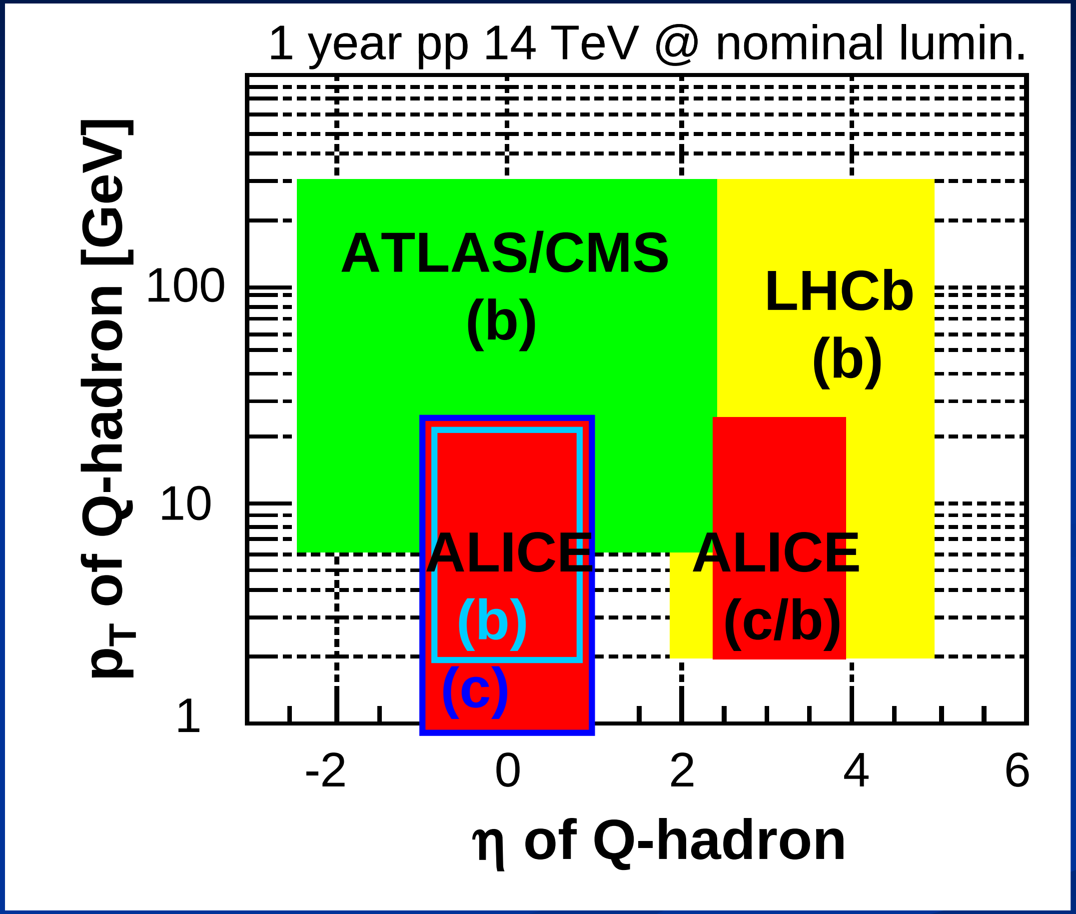


- ALICE “baseline”: pQCD at NLO (MNR) for pp + binary collision scaling + shadowing (large spread in predictions…):

	pp	*pPb (min bias)*	*PbPb (5% central)*
√s (TeV)	14	8.8	5.5
N_{cc}	0.16	0.8	115
N_{bb}	0.007	0.03	4.6

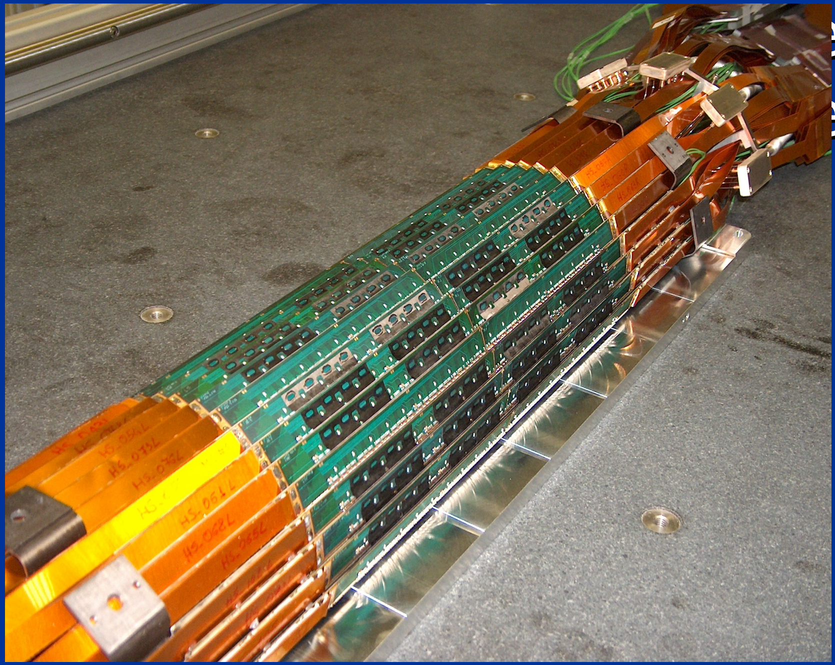
Acceptance for heavy flavours

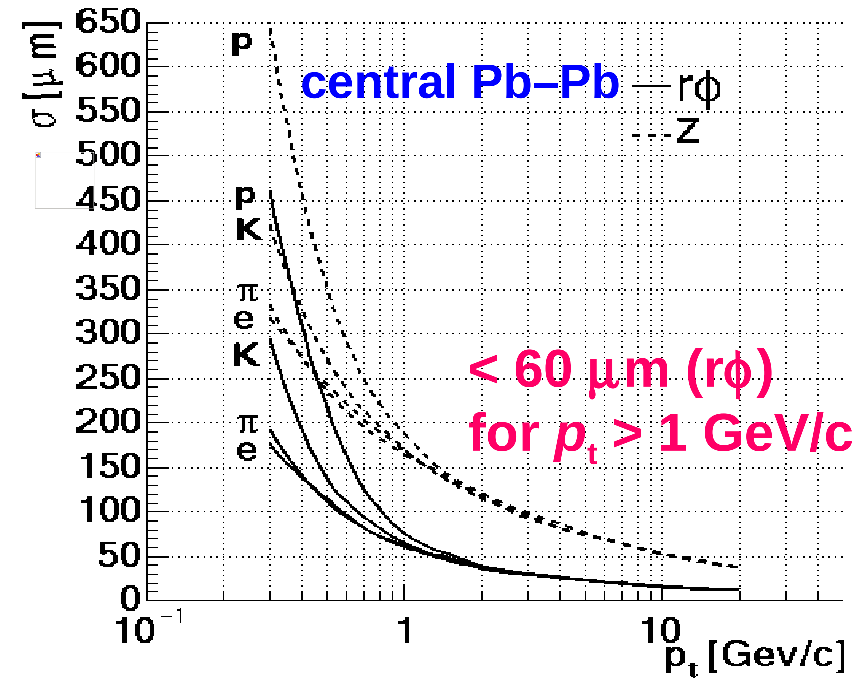
- ALICE channels:
  - electronic ($|\eta|<0.9$)
  - muonic ($-4<\eta<-2.5$)
  - hadronic ($|\eta|<0.9$)
- ALICE coverage:
  - low-p_T region
  - central and forward rapidity regions
- Precise vertexing in the central region to identify D ($c\tau \sim$ 100-300 μm) and B ($c\tau \sim$ 500 μm) decays



Impact parameter resolution

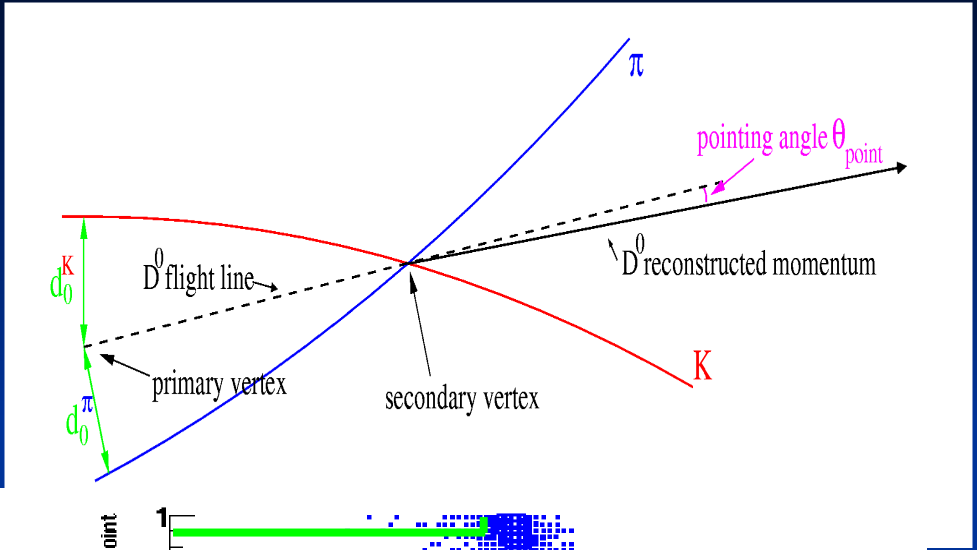
- Resolution on track impact parameter (= Distance of Closest Approach between track and primary vertex)
  - Mainly provided by the 2 innermost ITS layers equipped with silicon pixel detectors (rϕ: 50 μm, z: 425 μm)

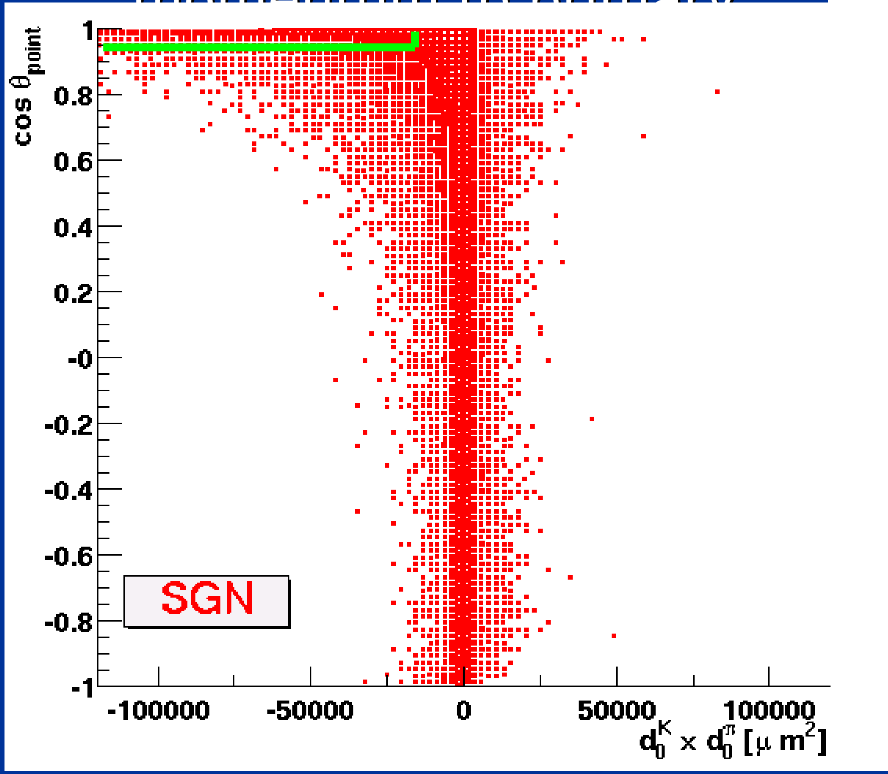


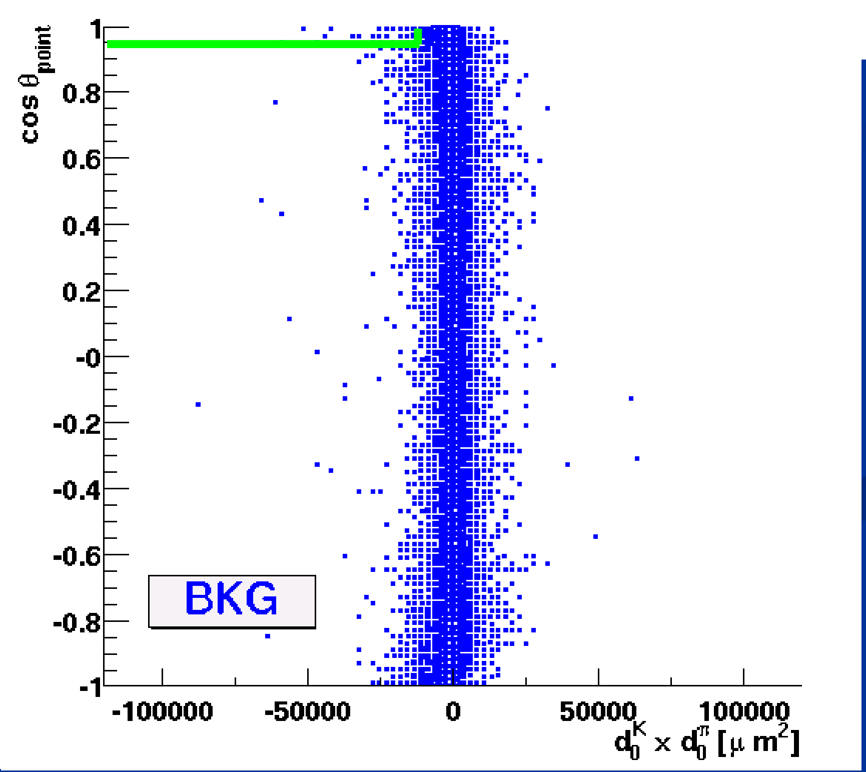


$D^0 \to K^-\pi^+$: selection

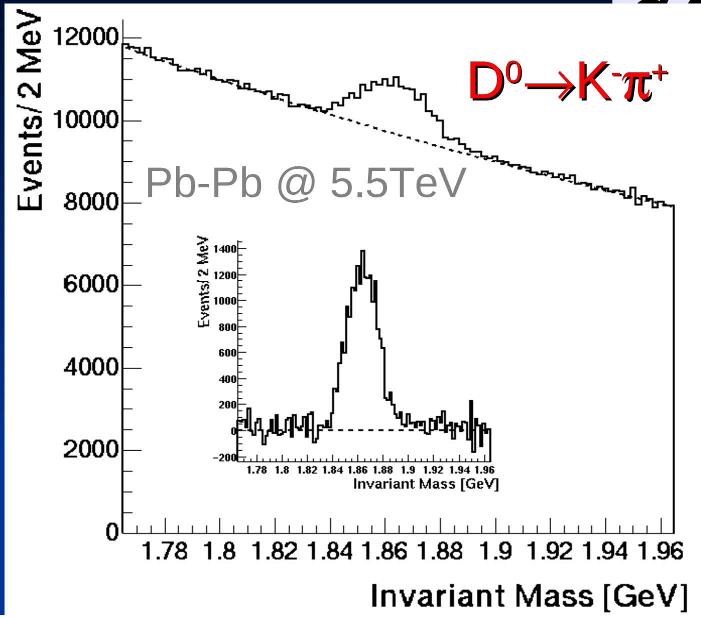
- Pair of opposite sign charged tracks:
  - large and opposite sign impact parameter
  - good pointing of reconstructed D momentum to primary

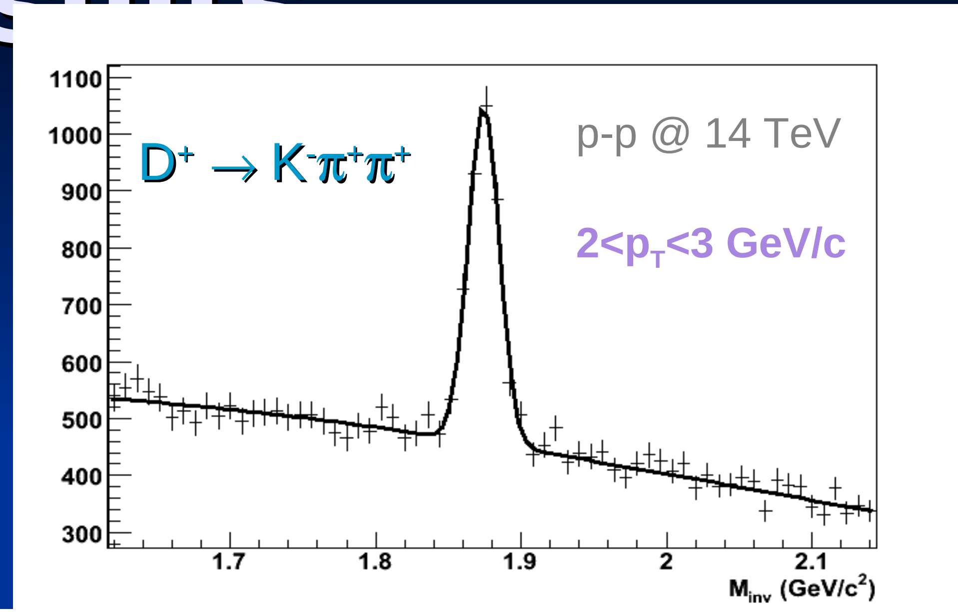


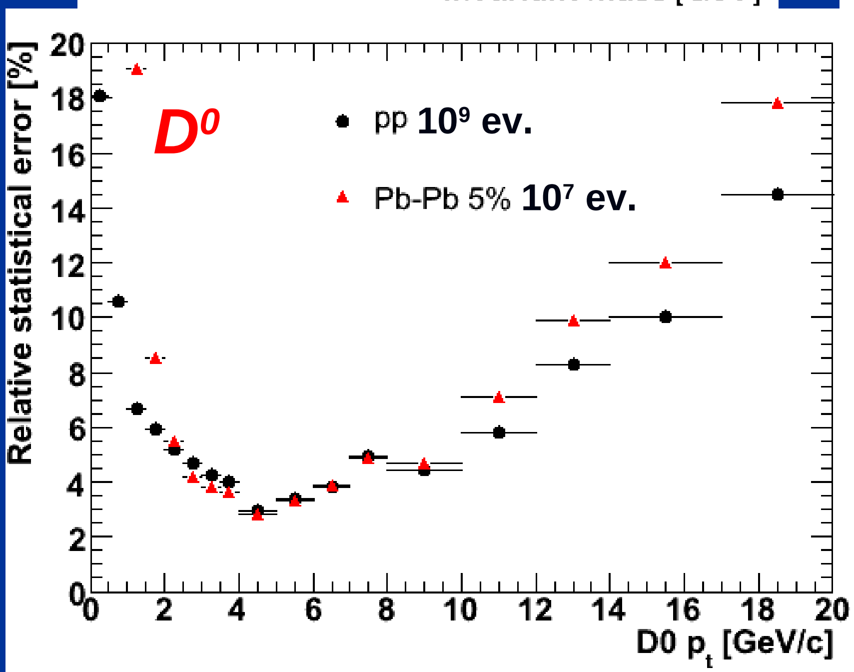


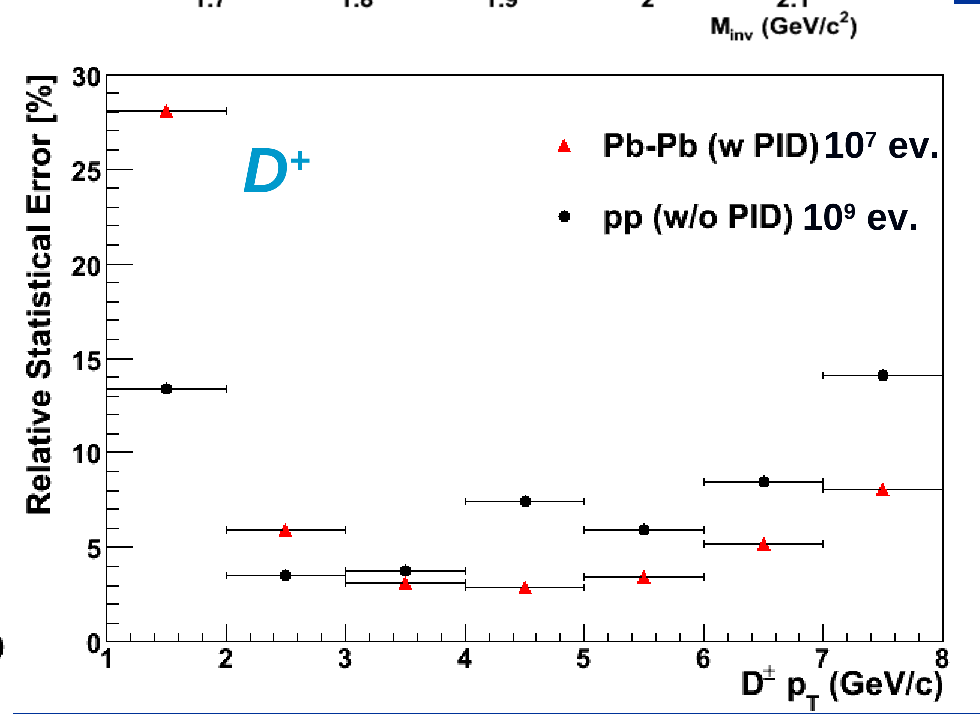


D^+ and D^0 : expected results







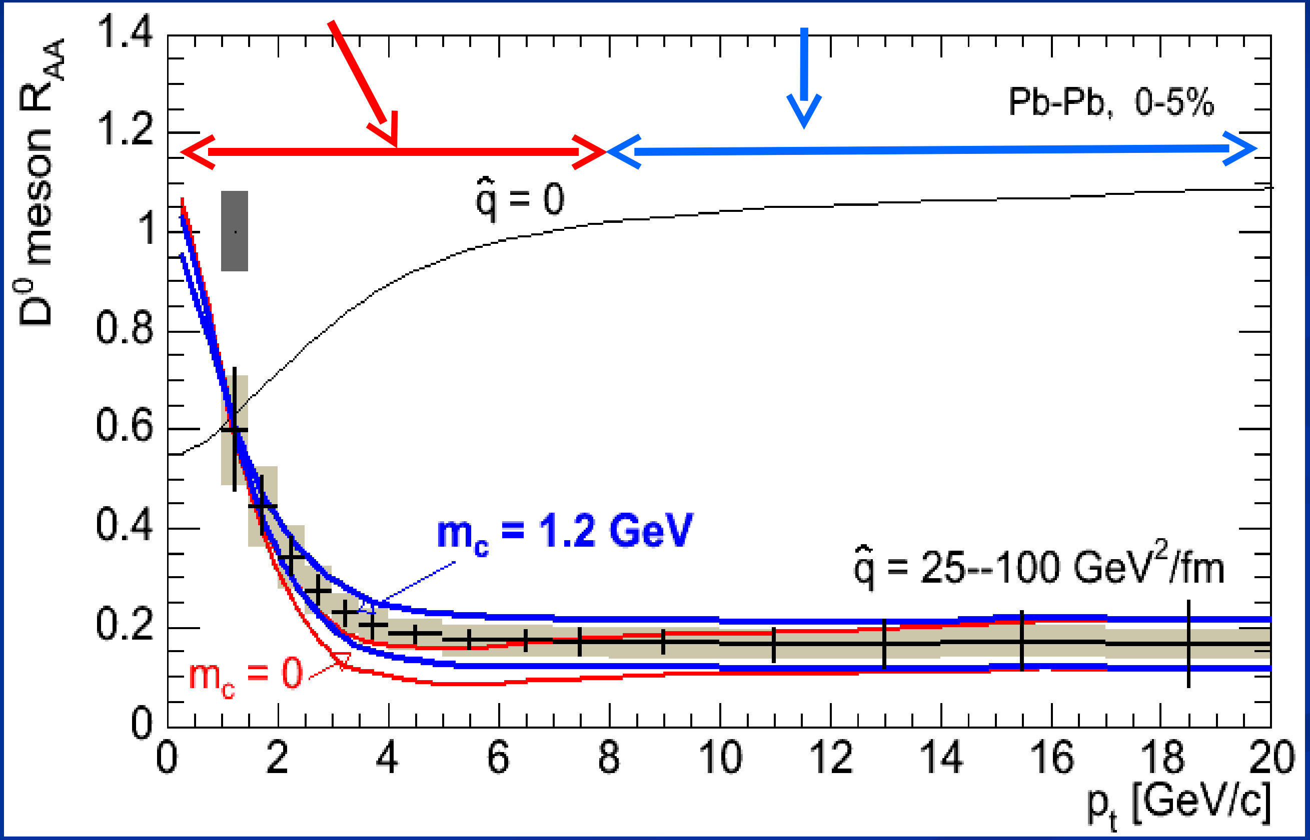


$D^0 \rightarrow K^-\pi^+$: more results

- 1 year at nominal luminosity, i.e. 1 month → 10^7 central Pb-Pb events and 10 months → 10^9 pp events

Low p_T (< 6–7 GeV/c)
Also nuclear shadowing

'High' p_T (6–15 GeV/c)
Only parton energy loss

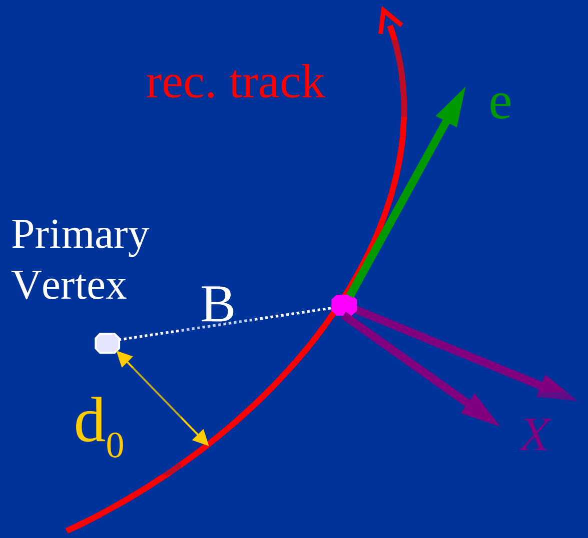


Measuring beauty via electrons

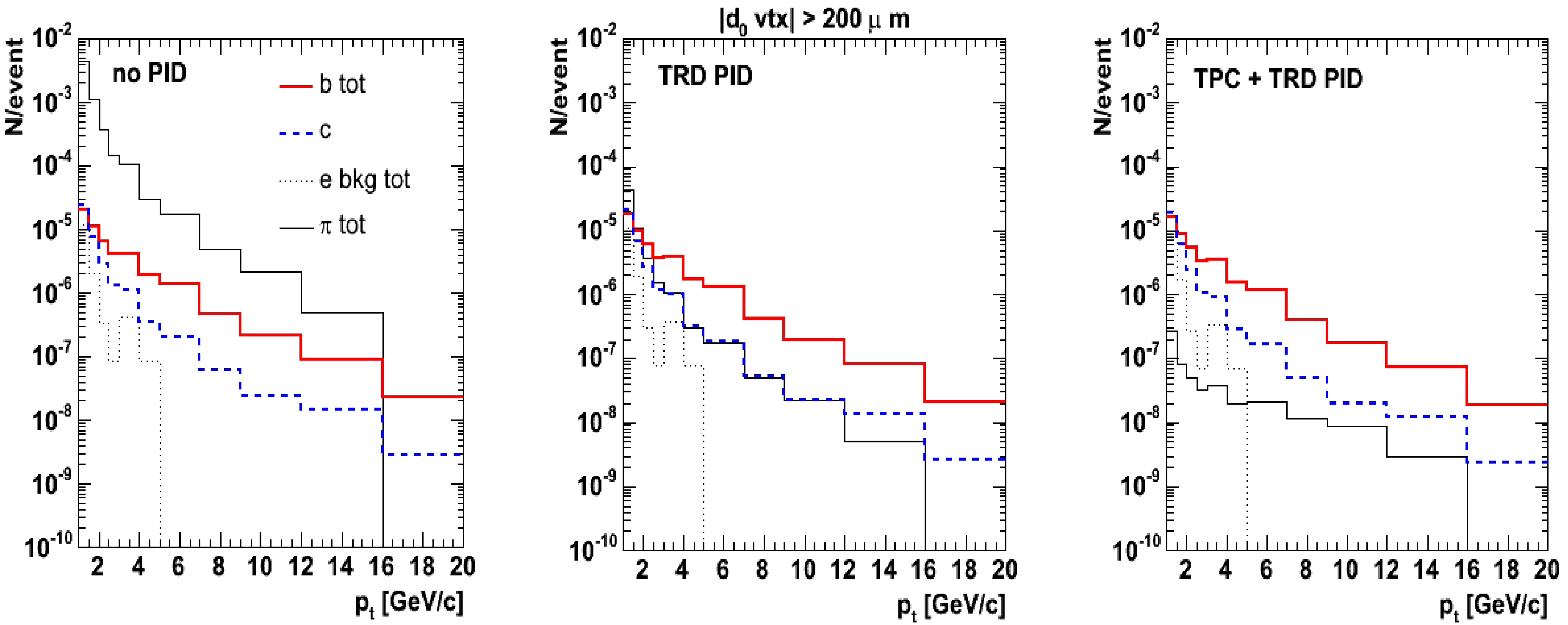
- Expected yields of charm (b.r.: 10%) and beauty (b.r.: 11% +10% as b→c→e) decay electrons:

system : $\sqrt{s_{NN}}$:	Pb-Pb (0-5% centr.) 5.5 TeV	pp 14 TeV
$N_{tot}^{Q\overline{Q}}$	**115 / 4.6**	**0.16 / 0.007**
N^{e}	**23 / 1 (+1)**	**0.03 / 0.0015 (+0.0015)**
$N_{\lvert\eta\rvert<0.9}^{e}$	**6 / 0.25 (+0.25)**	**0.008 / 0.0004 (+0.0004)**

b quark has cτ ≈ 500 μm
→ decay electrons have
d0 ~ few-100 μm

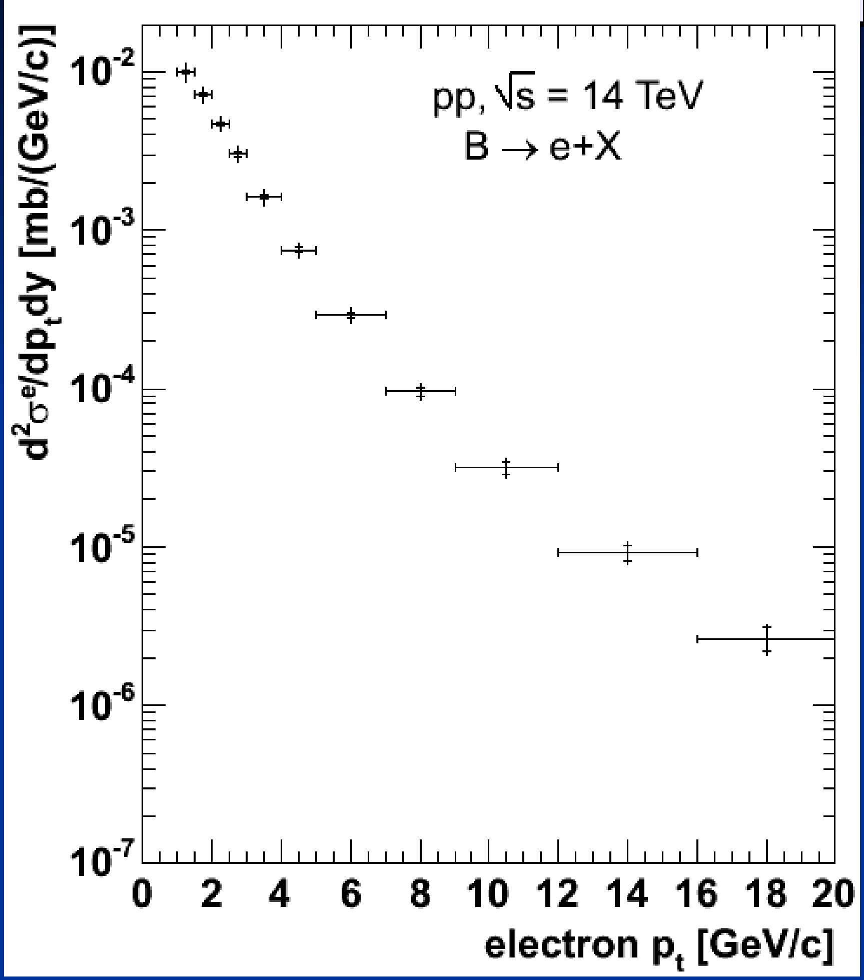


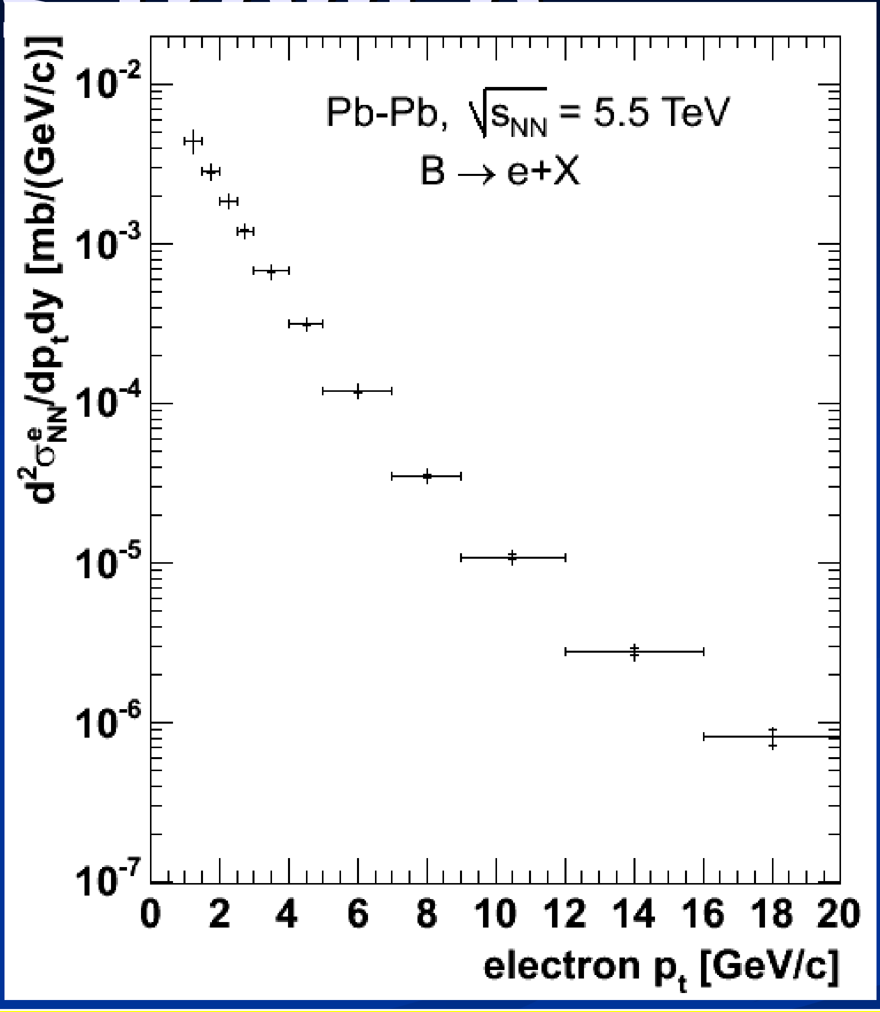
Electron identification vs p_T



Beauty signal dominates!
at least at high p_T....

Cross-sections of electrons from b

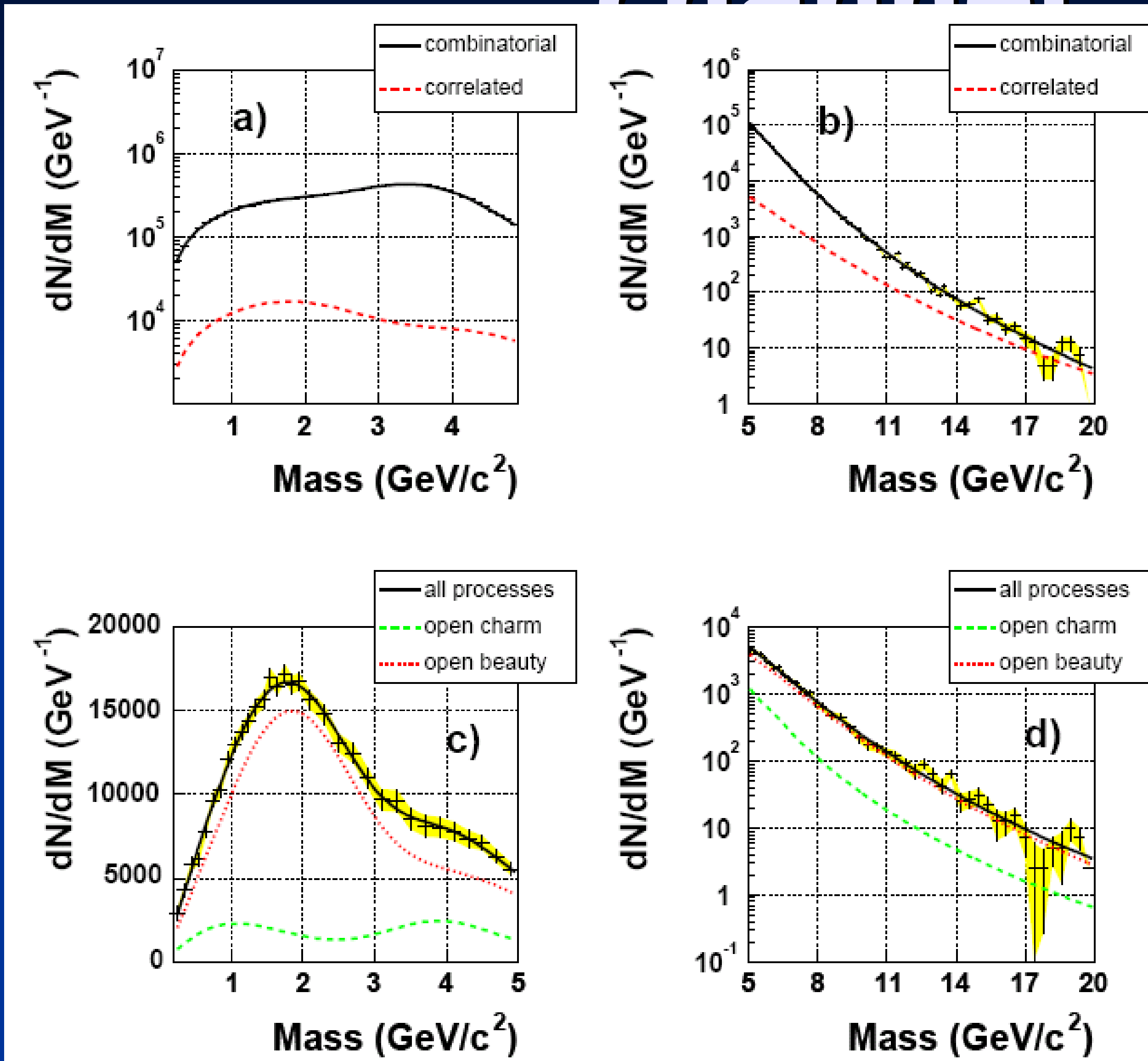




1 year at nominal luminosity
(10^7 central Pb-Pb events,
10^9 pp events)

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

Beauty in the dimuon channel



Central Pb-Pb (0-5%)
1 month of data taking
p_T^{μ}>1.5 GeV/c

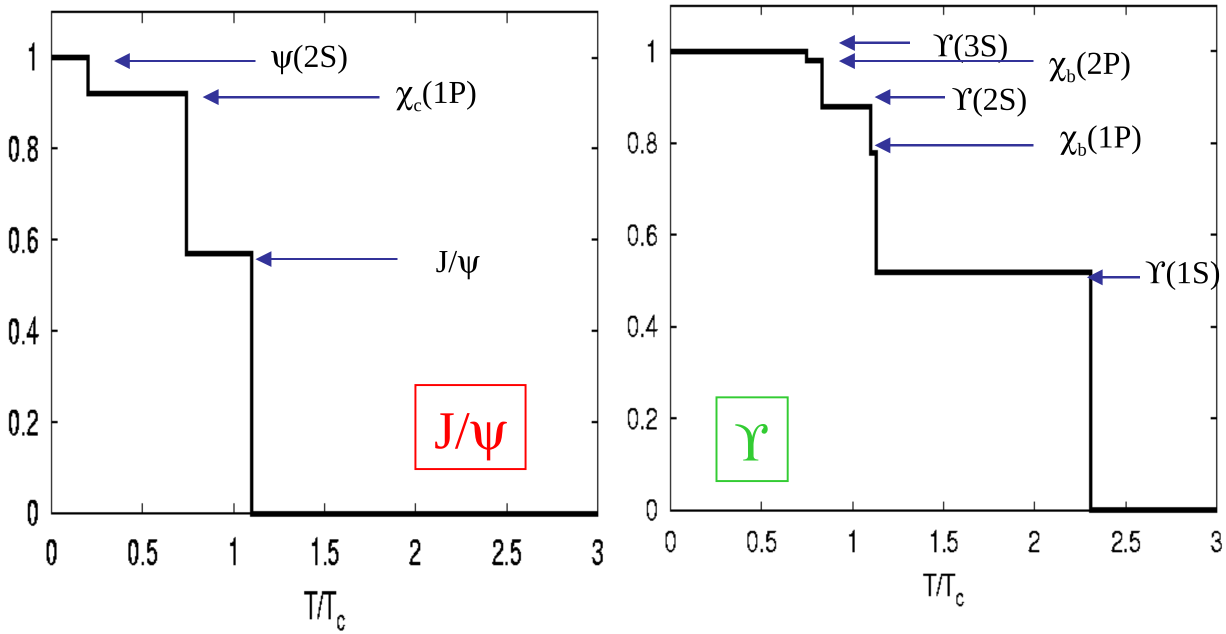
Before
background subtraction

$$B^+ \to \overline{D^0}\,\ell_1^+ \nu_\ell$$
$$\hookrightarrow \ell_2^- X'$$
$$\overline{B^0} \to D^+ \ell_3^- \overline{\nu_\ell}$$
$$\hookrightarrow \ell_4^+ X''$$

After
background subtraction

Heavy quarkonia

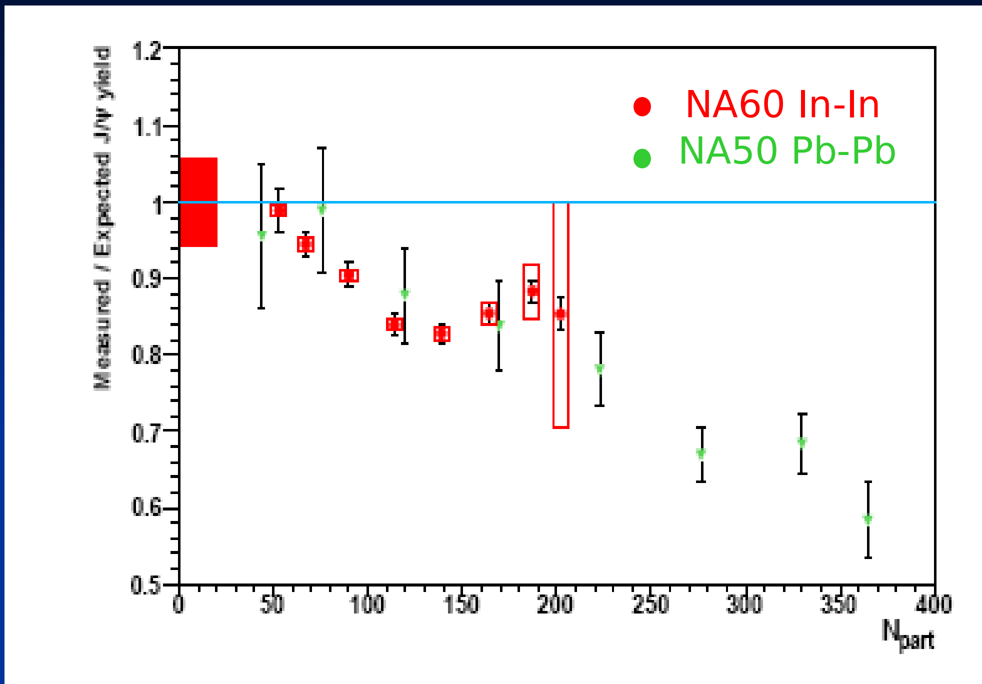
- Sequential suppression predicted by Lattice QCD calculations of q-q potential Debye screening

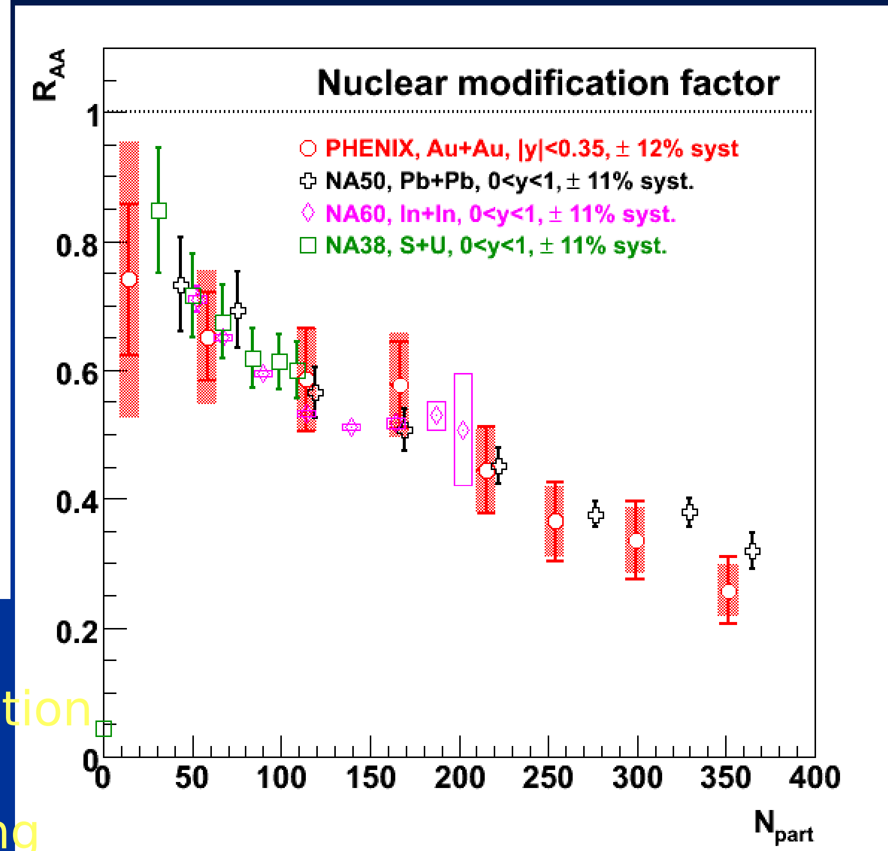


Digal et al., Phys.Rev. D64 (2001) 094015

Every state has a typical dissociation threshold; usually one measures the strongly bound states, but other states may have nonzero branching ratios to strongly bound ones

SPS and RHIC J/ψ results

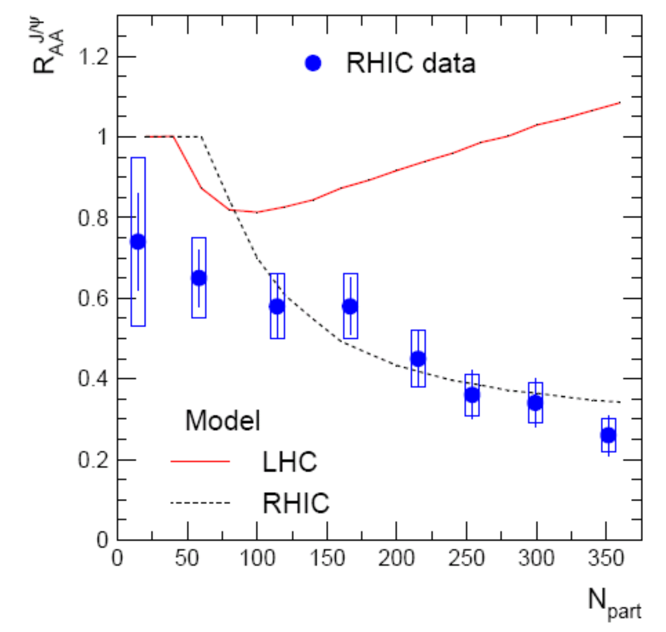




bs. **suppression** exceeds nuclear absorption
nset of the suppression at $N_{part} \sim 80$
omparison between systems → N_{part} scaling
urprising agreement SPS/RHIC R_{AA}, despite:
- different √s
- different shadowing
- different nuclear absorption

Quarkonia in ALICE

- Quarkonia in ALICE will be measured at:
  - Midrapidity (central barrel, via electron tagging in the TRD)
  - Forward rapidity (2.5<y<4, in the muon arm)
- Role of the large charm quark multiplicity:
  - Will J/ψ regeneration dominate the picture for charmonium ? (RHIC results still not conclusive, at this stage)



Example of a prediction for J/ψ R_{AA} at RHIC and LHC

- Bottomonium physics:

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

  - Will the tightly bound ϒ(1S) be melted at the LHC ?

Dimuons – expected statistics

Stat	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

Numbers refer to

$L = 5 \times 10^{26}$ cm^{-2}s^{-1}

10^6 s running time

Pb-Pb central collisions

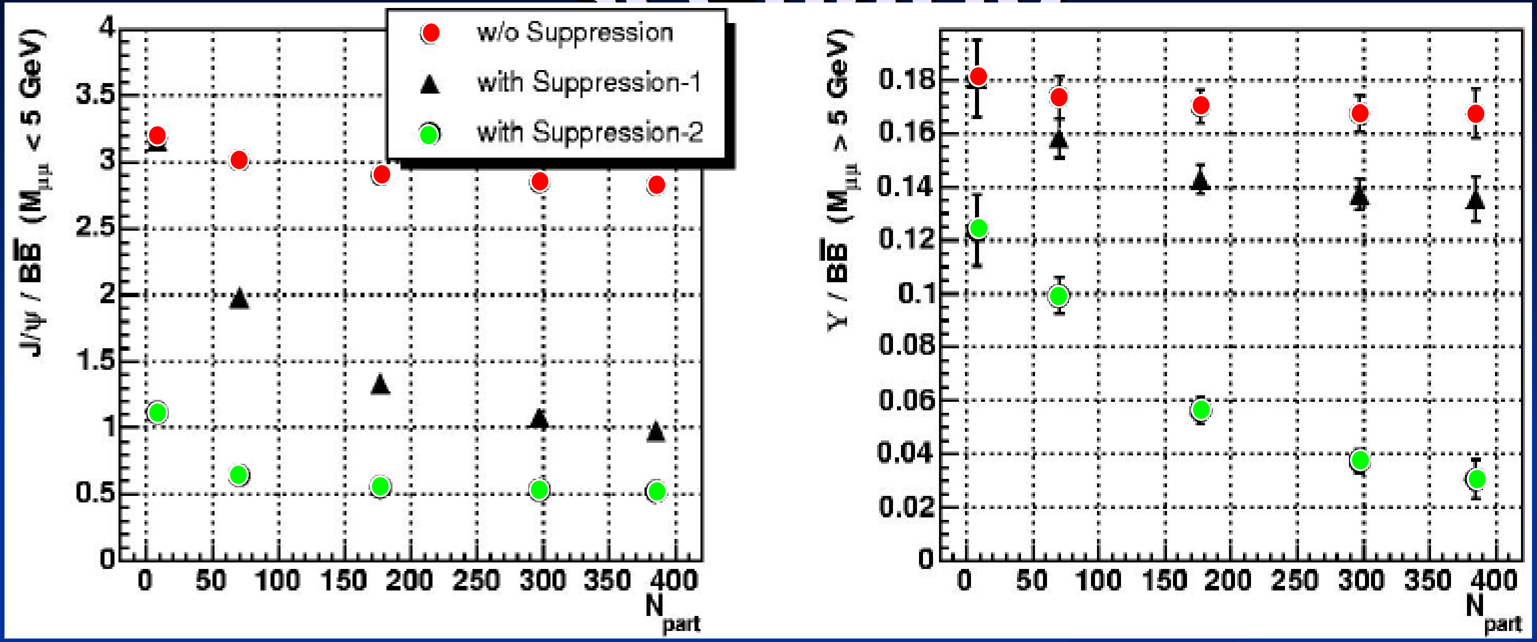
no suppression,
no enhancement

nificances not dramatically different between J/ψ and ϒ
→ smaller statistics compensated by drastic background reduction

orst situation for the ψ' : statistics ~ ϒ, but much larger background

ituation improves for the J/ψ when moving towards peripheral vents (background mainly combinatorial)
or the ϒ, no significant centrality dependence
background dominated by correlated open beauty)

Dimuons – suppression scenario



- Suppose $\sigma_{abs}^{J/\psi}=0$ (reasonable, extrapolating from RHIC ?)
- No b quark energy loss
- Take into account feed-down from higher resonances

- Suppression-1
  - T_c=270 MeV
  - T_D/T_C=1.7 (4.0) for J/ψ (Υ)
- Suppression-2
  - T_c=190 MeV
  - T_D/T_C=1.21 (2.9) for J/ψ (Υ)

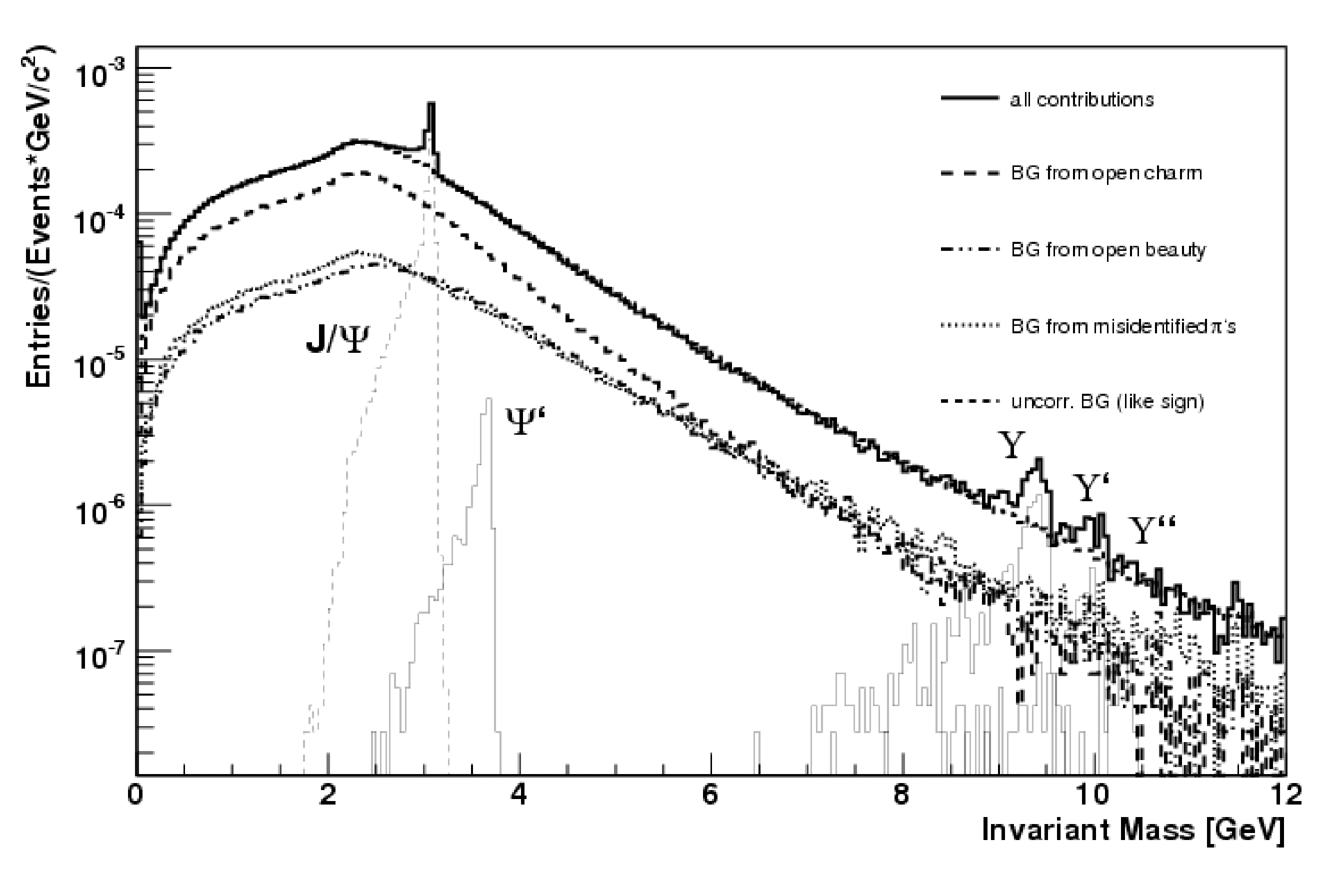
Good sensitivity to input parameters, for various scenarioes

Quarkonia in the dielectron channel

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

$L = 5\times10^{26}\ cm^{-2}s^{-1}$

10^6 s running time

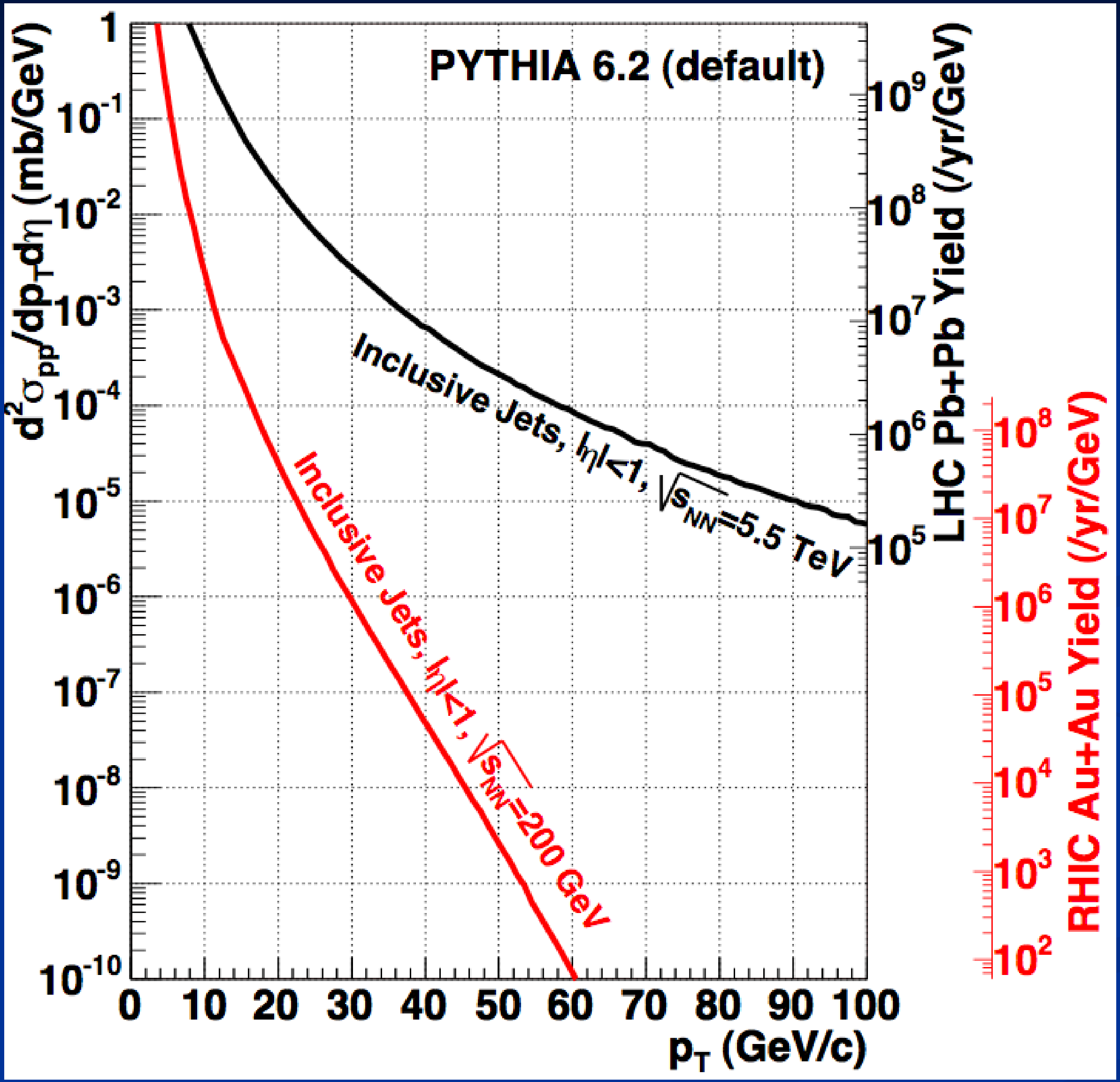


10% most central events

Background from misidentified π likely to be suppressed (quenching)

$dN_{ch}/d\eta = 3000$

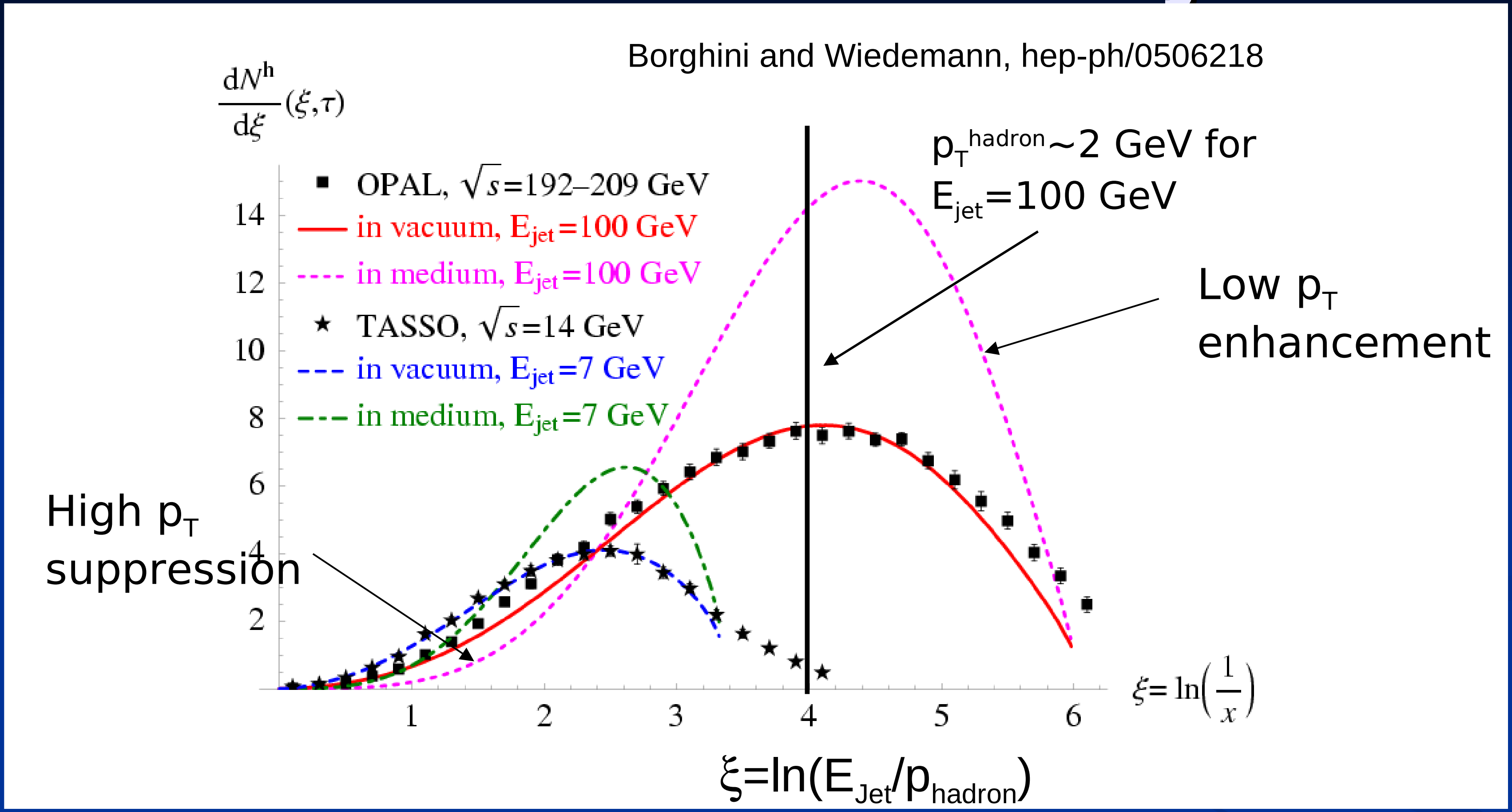
Jets at LHC



- Contrarily to what happens at RHIC, jet rates at high energies become significant
- They can more easily be distinguished from the background energy of the underlying event

Jet study will have much higher sensitivity to the medium properties with respect to R_{AA}

Medium effects on jets

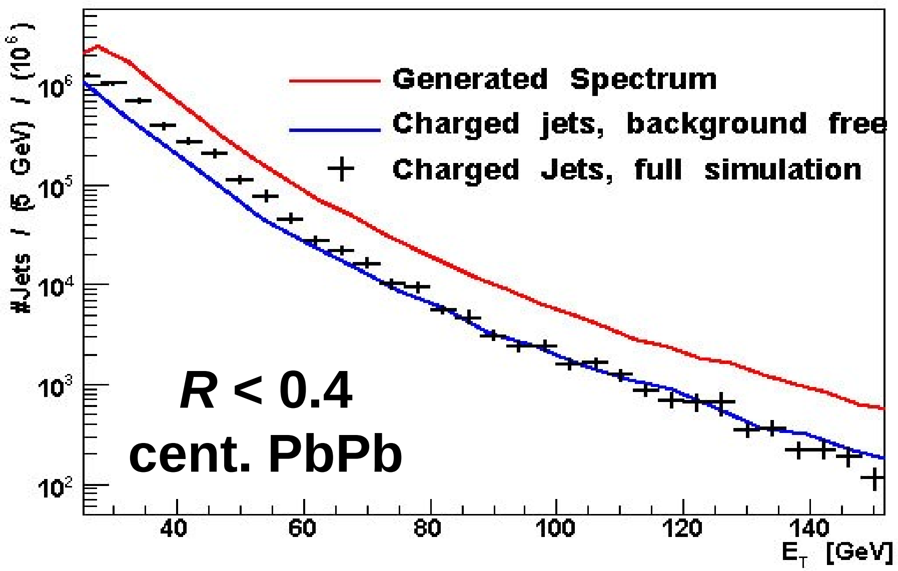


- Fragmentation strongly modified by medium at p_T^{hadron}~1-5 GeV even for the highest energy jets
- Even a moderate increase of the jet size should be observed

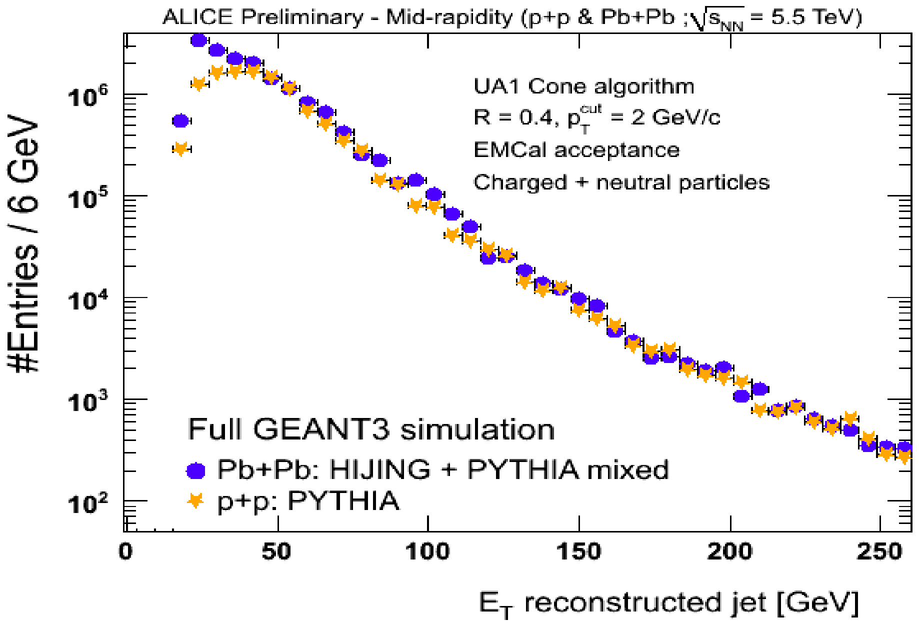
Expected jet yields in ALICE

tistics corresponding to 1 PbPb year = 10^6 s

Charged Jets



Charged + neutral



- In AA, high-p_T (calorimetry) and low-p_T capabilities needed for "unbiased" measurement of parton energy. Strengths of ALICE:

  - Excellent low-p_T capabilities to measure particles from medium induced radiation.
  - PID to measure the particle composition of quenched jets

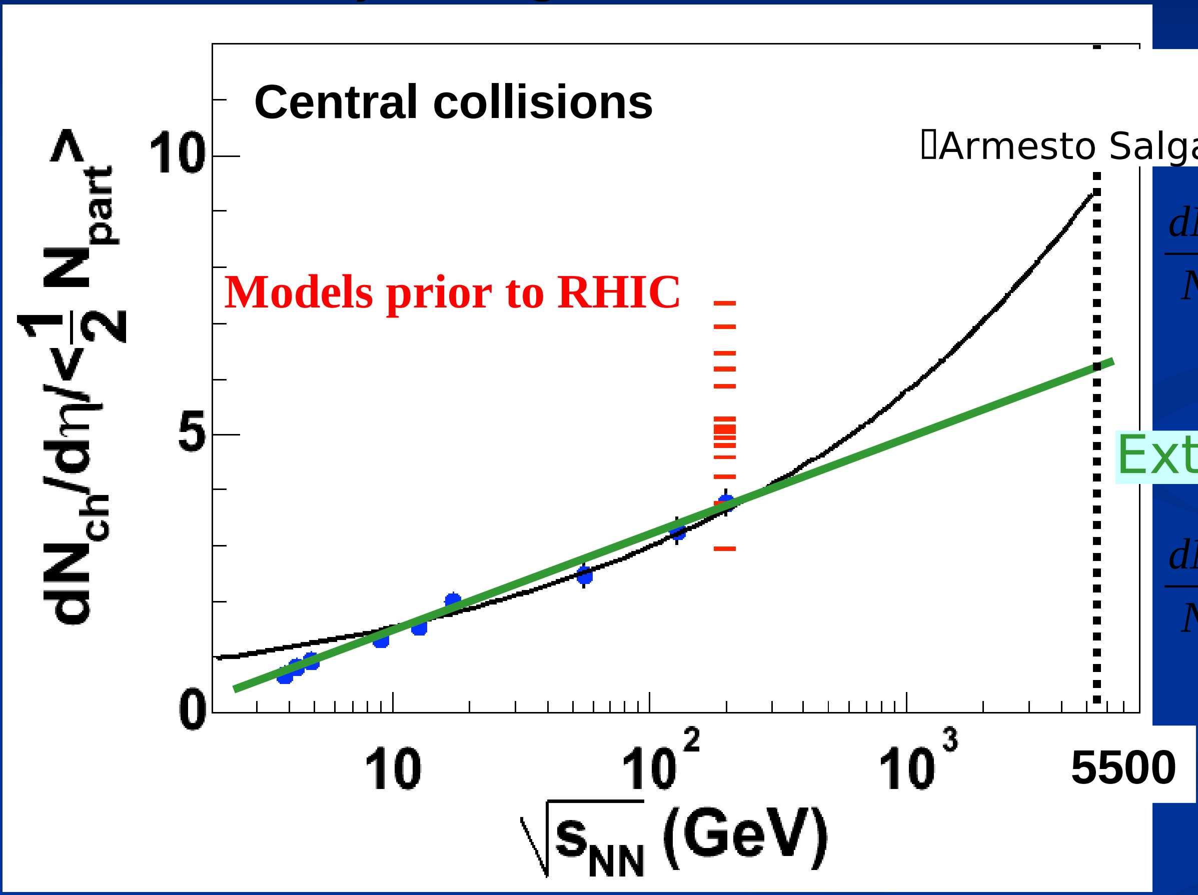
(dedicated p+p experiments have larger E_T reach)

Soft probes

- charged multiplicity
- flow
- particle spectra
- resonances
- *femtoscopy*
- *event-by-event*

Charged multiplicity at the LHC

- Extrapolation of $dN_{ch}/d\eta_{max}$ vs $\sqrt{s}$
  - Fit to $dN/d\eta \propto \ln s$ …
  - … or Saturation model ($dN/d\eta \propto \sqrt{s}^{\lambda}$ with $\lambda=0.288$)
  - Clearly distinguishable with the first 10k events at the LHC



Saturation model

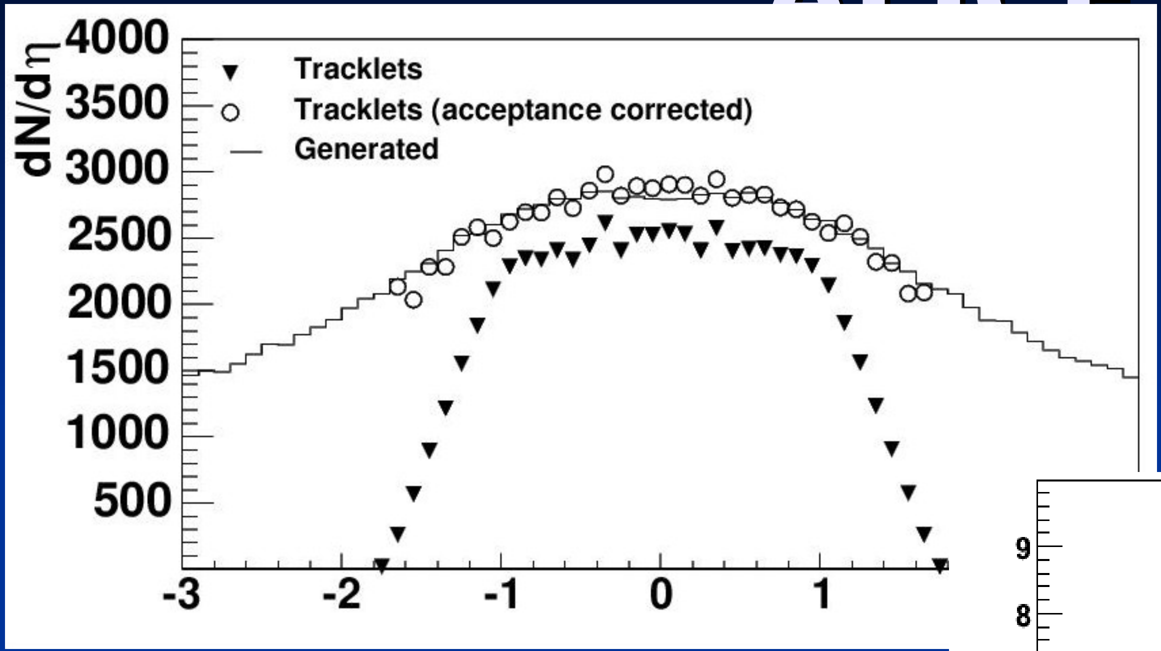
Armesto Salgado Wiedemann, PRL 94 (2005) 022002

$$\left.\frac{dN_{ch}/d\eta}{N_{part}/2}\right|_{\eta=0} \approx 8.2 \Rightarrow \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 1650$$

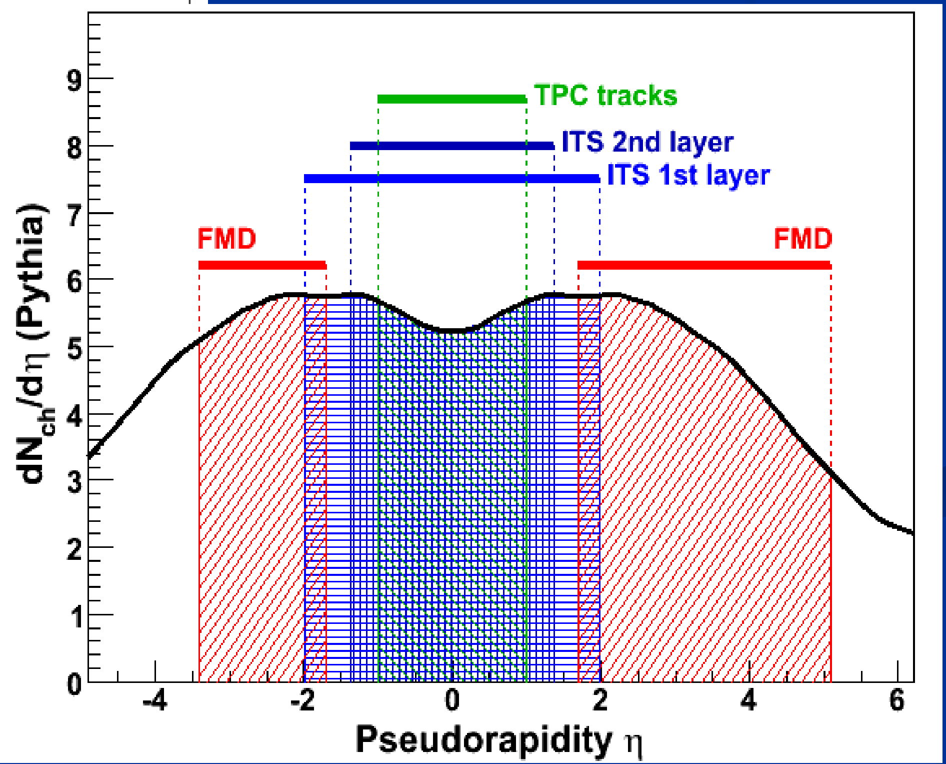
Extrapolation of $dN/d\eta \propto \ln s$

$$\left.\frac{dN_{ch}/d\eta}{N_{part}/2}\right|_{\eta=0} \approx 5.5 \Rightarrow \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \approx 1100$$

Charged multiplicity in ALICE

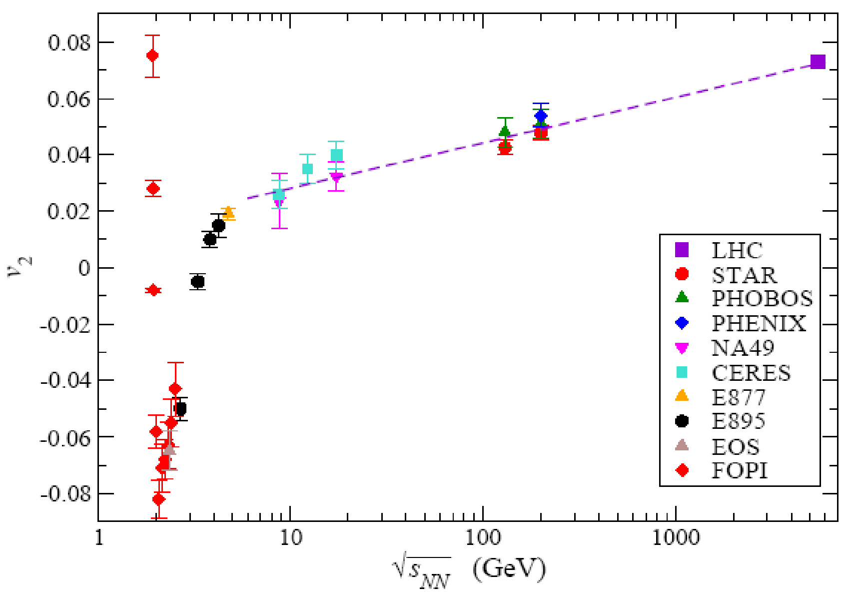


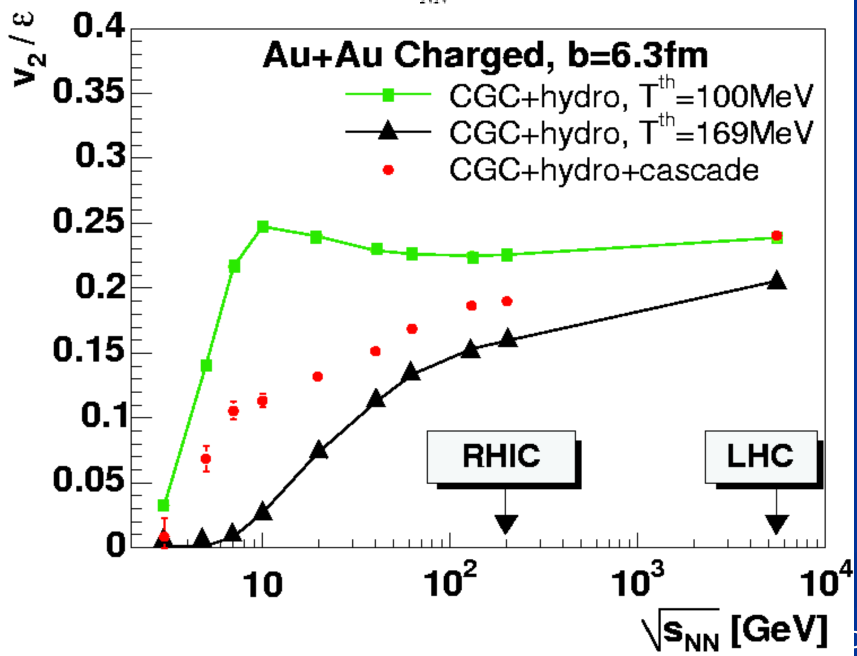
Reconstructed $dN_{ch}/d\eta$ with tracklets in SPD (generated $dN_{ch}/d\eta = 3000$)



Wide rapidity coverage provided by ITS (SPD), TPC in the central region & FMD in the forward region

Flow





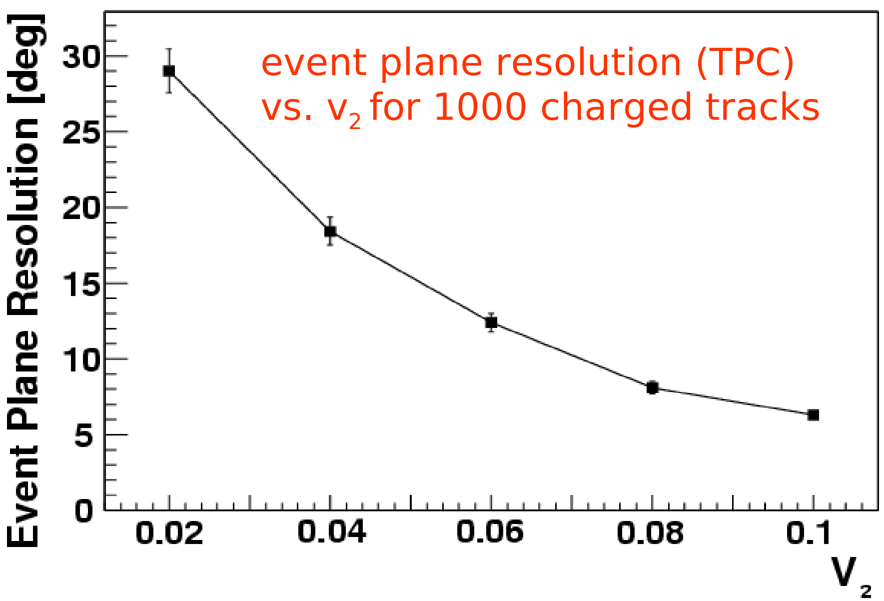
v_2 (elliptic flow) dependence on √s

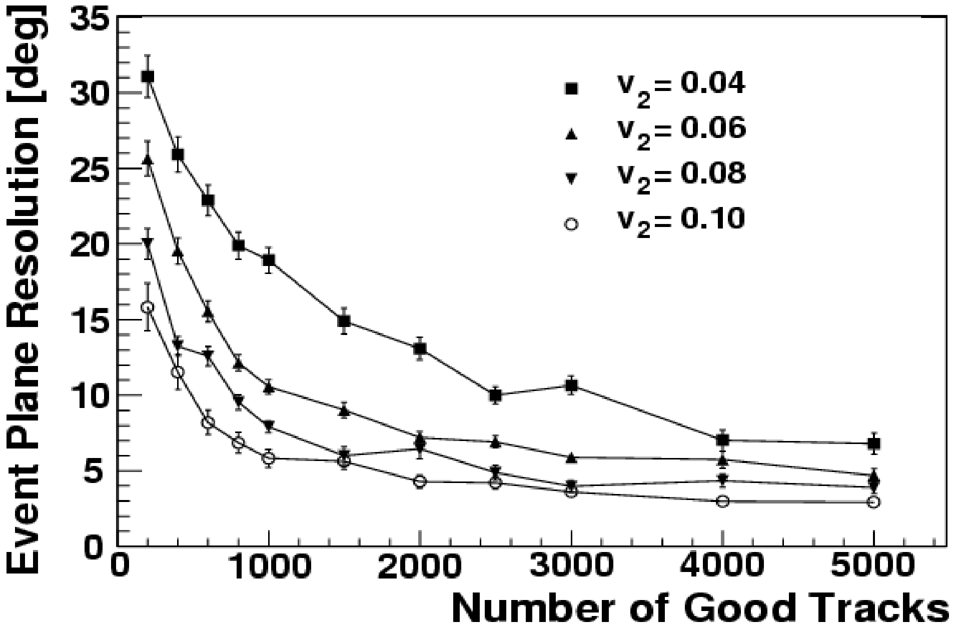
Expect $v_2(0)$ @ ALICE ~ 0.08

Large signal → easy measurement
Beware of non-flow contributions (jets…)!

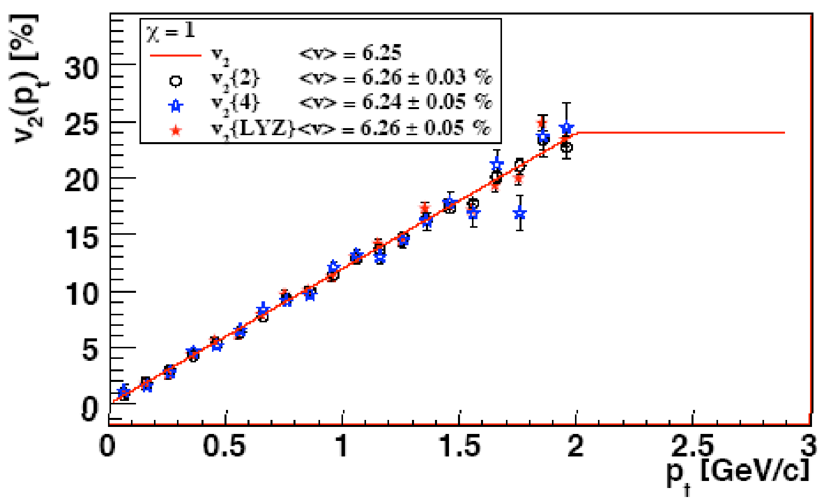
Contribution by QGP phase much larger than at lower energies

Flow: event plane & other methods





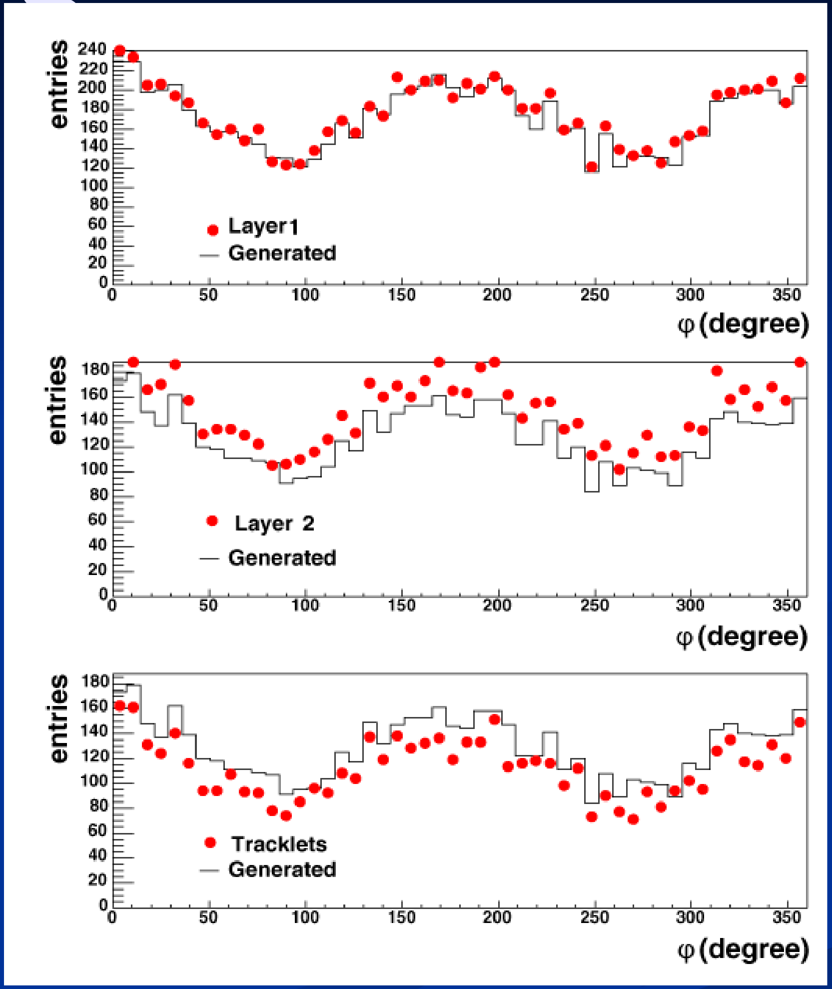
v_2 vs p_T
for $\langle v_2 \rangle = 0.0625$



Reaction Plane
Cumulants
Lee Yang Zeroes

Flow with inner ITS layers

- SPD alone useful for low multiplicity events, and has higher acceptance wrt TPC (low p_T threshold ~15 MeV)
- Simulations suggest
  - flow for negative and positively charged particles separately
  - coarse p_T binning may be possible



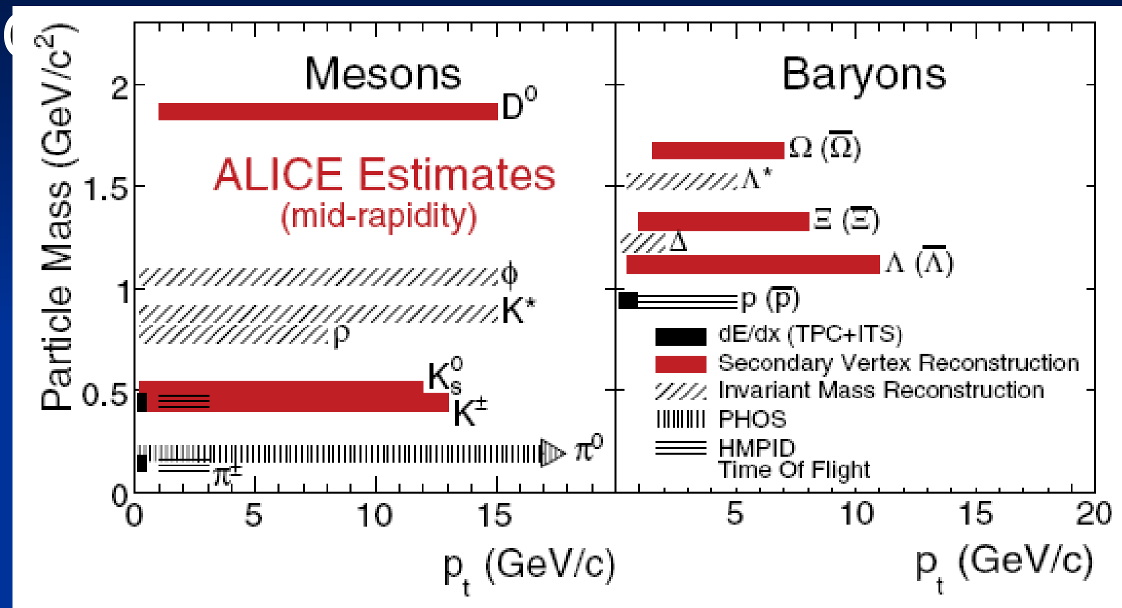
Generated			Clusters Layer 1		Tracklets	
$dN/d\eta$	v_2	Ψ_2 [degree]	v_2	Ψ_2 [degree]	v_2	Ψ_2 [degree]
1400	0.05	0	0.06 ± 0.01	-2.5 ± 4	0.07 ± 0.01	-7 ± 4
2800	0.05	0	0.06 ± 0.01	2 ± 3	0.06 ± 0.01	-0.3 ± 3
5500	0.05	0	0.058 ± 0.005	-2 ± 3	0.058 ± 0.005	-8 ± 3
1400	0.10	0	0.11 ± 0.01	0.4 ± 3	0.12 ± 0.01	-1 ± 3
2800	0.10	0	0.114 ± 0.009	-2.4 ± 2	0.115 ± 0.009	-1 ± 2
2800 (no field)	0.10	0	0.113 ± 0.009	0.4 ± 2	0.114 ± 0.009	-0.9 ± 2
5500	0.10	0	0.101 ± 0.006	-3 ± 2	0.104 ± 0.007	-3 ± 2

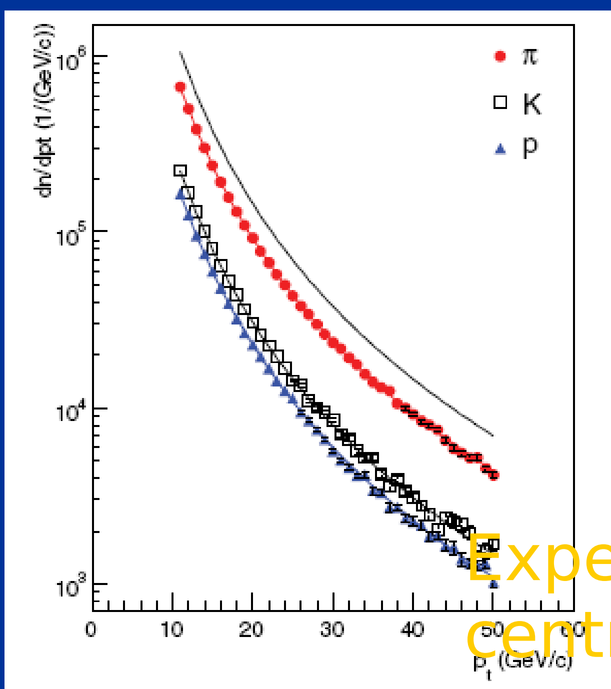
In addition, FMD and PMD will measure flow at forward rapidities

Layer 1 ▪ η 2.0 > ▪
Layer 2 ▪ η 1.4 > ▪

Particle spectra

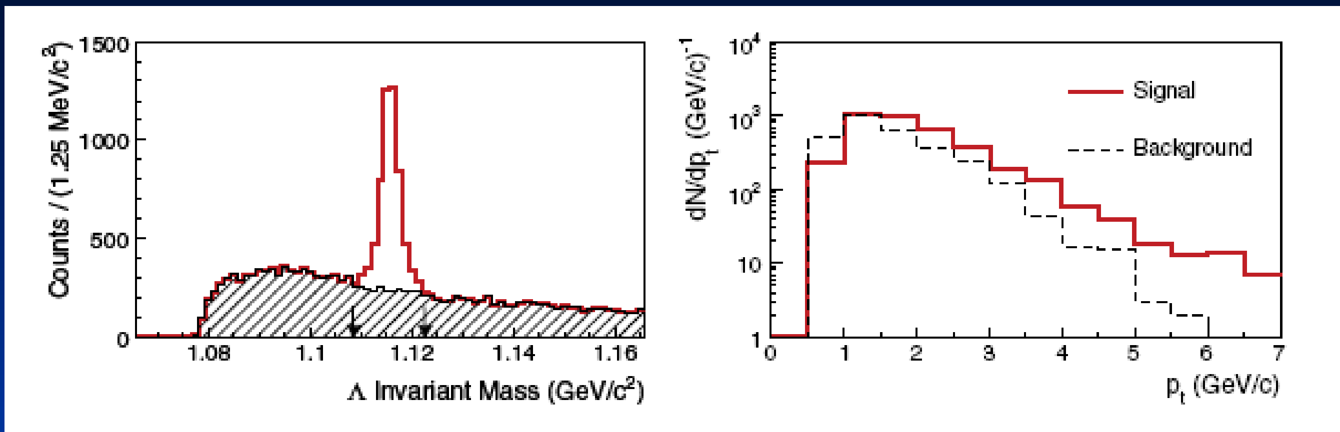
- Transverse momentum ranges for particle identification in ALICE



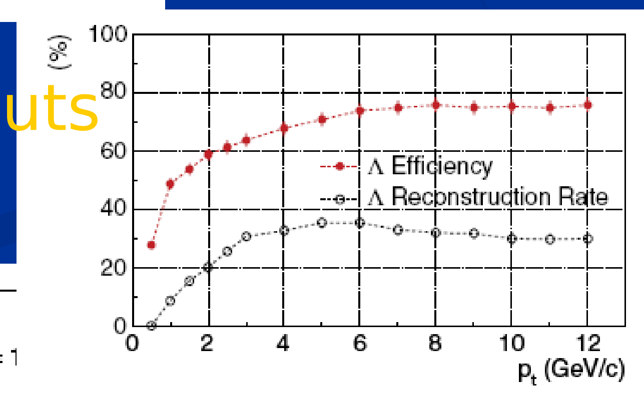


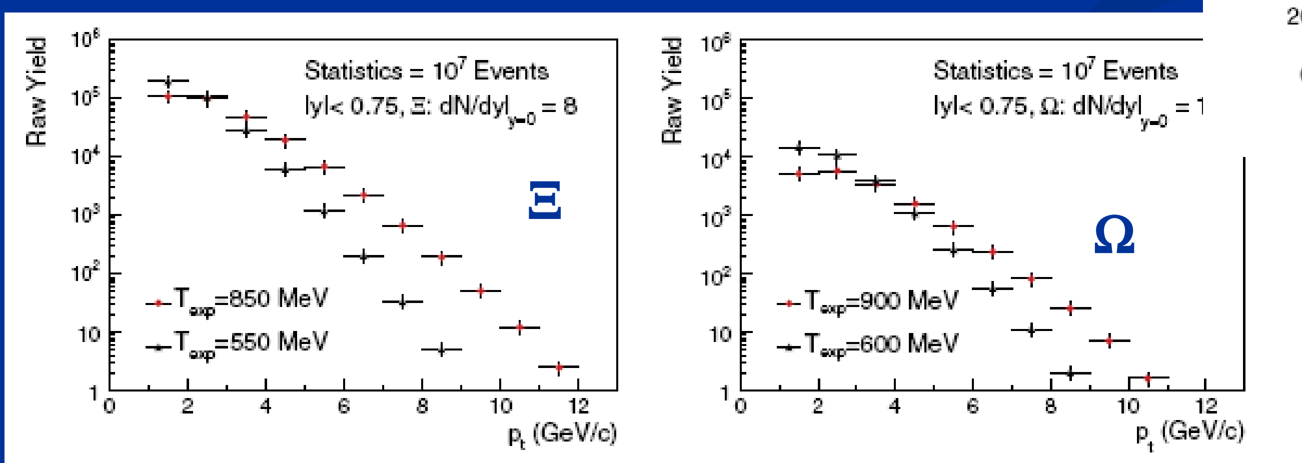
Expected charged hadrons yields for 10^7 Pb central collisions (TPC PID on statistical basis)

Strange particle spectra



Λ: optimized, p_T-dependent selection cuts



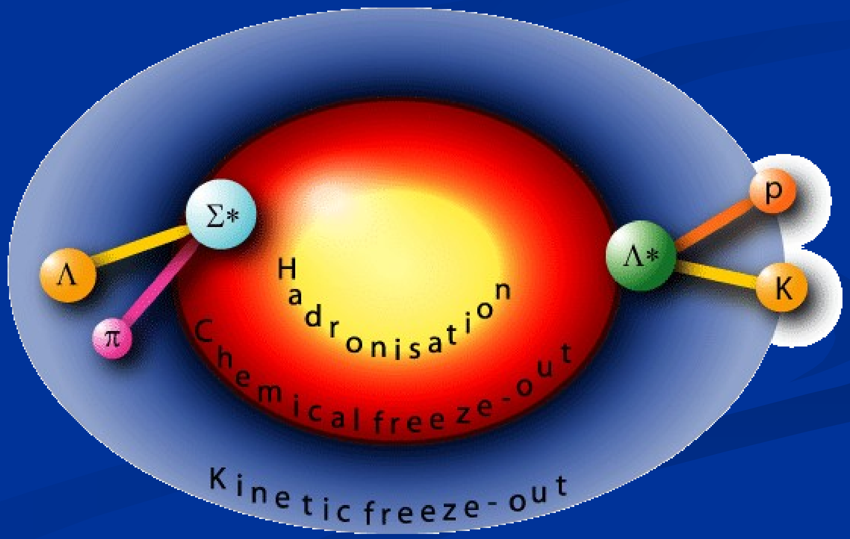


Resonances

Resonance	Life-time [fm/c]
ρ	1.3
Δ^{++}	1.7
$f_0(980)$	2.6
K*(892)	4.0
Σ(1385)	5.7
Λ(1520)	13
ω(783)	23
ϕ(1020)	45

resonance	mass [MeV]	width [MeV]	quark content
$K^{*0}(892)$	896.10 ± 0.28	50.5 ± 0.6	$\lvert d\bar{s}\rangle$
$K^{*+}(892)$	891.66 ± 0.26	50.8 ± 0.9	$\lvert u\bar{s}\rangle$
$\rho^-(770)$	768.3 ± 0.5	151.5 ± 1.2	$\lvert d\bar{u}\rangle$
$\rho^0(770)$	768.7 ± 0.7	152.4 ± 1.5	$1/\sqrt{2} \cdot (\lvert u\bar{u}\rangle - \lvert d\bar{d}\rangle)$
$\rho^+(770)$	768.3 ± 0.5	151.5 ± 1.2	$\lvert u\bar{d}\rangle$
$K^{*-}(892)$	891.66 ± 0.26	50.8 ± 0.9	$\lvert s\bar{u}\rangle$
$\bar{K}^{*0}(892)$	896.10 ± 0.28	50.5 ± 0.6	$\lvert s\bar{d}\rangle$
$\omega(783)$	781.94 ± 0.12	8.41 ± 0.09	$1/\sqrt{2} \cdot (\lvert u\bar{u}\rangle + \lvert d\bar{d}\rangle)$
$\phi(1020)$	1019.413 ± 0.008	4.43 ± 0.05	$\lvert s\bar{s}\rangle$

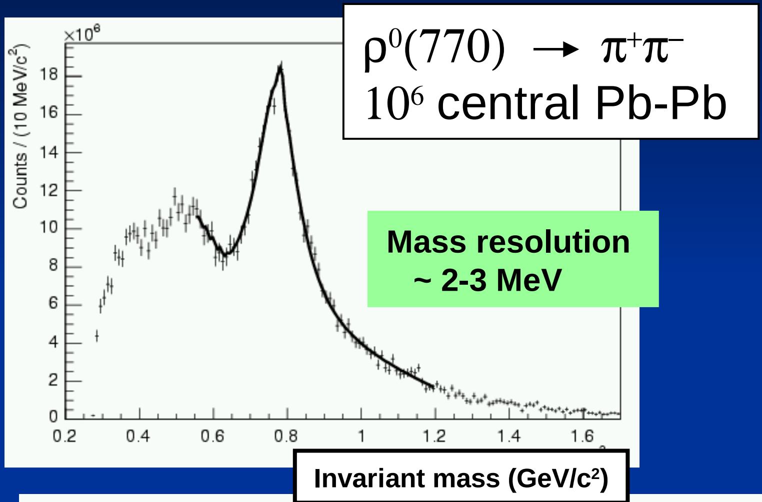
- Decay time comparable with (or even shorter than) QGP lifetime

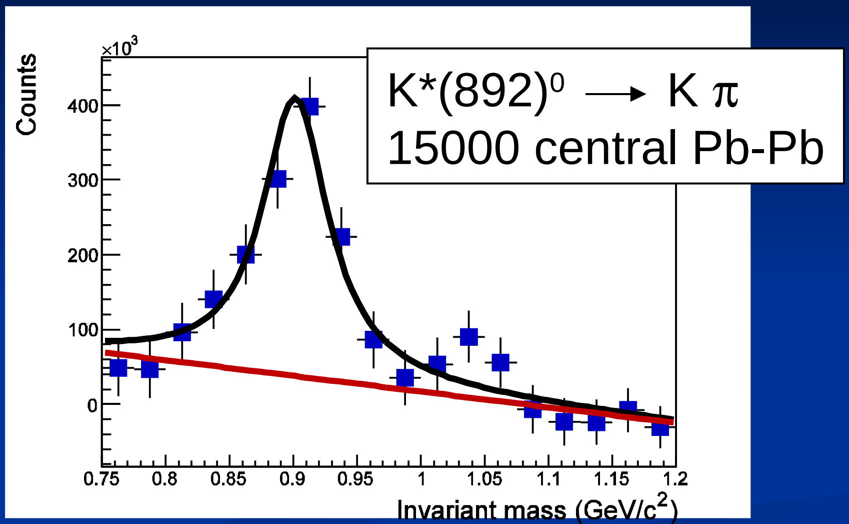


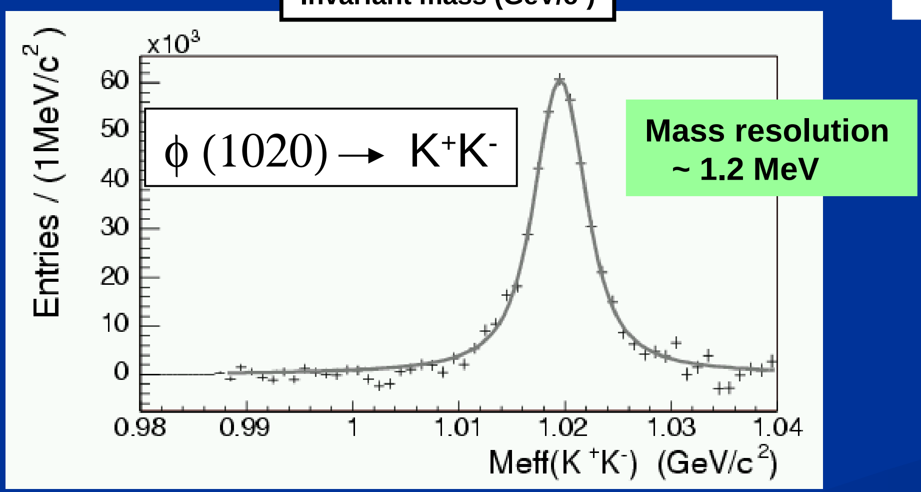
Resonances in ALICE

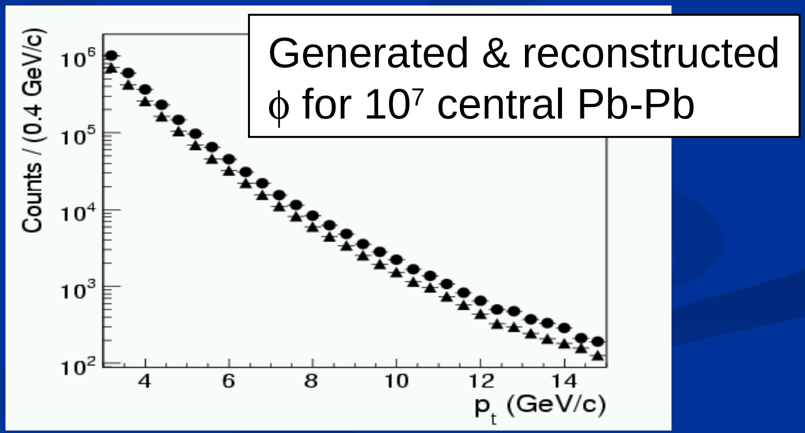
Invariant mass reconstruction, background subtracted (like-sign method)

mass resolutions ~ 1.5 - 3 MeV and p_T stat. limits from 8 (ρ) to 15 GeV (ϕ, K*)





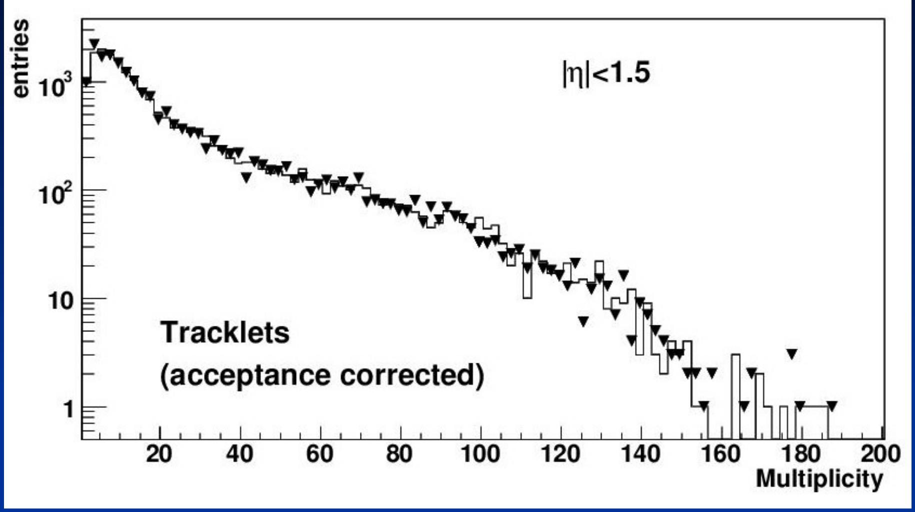


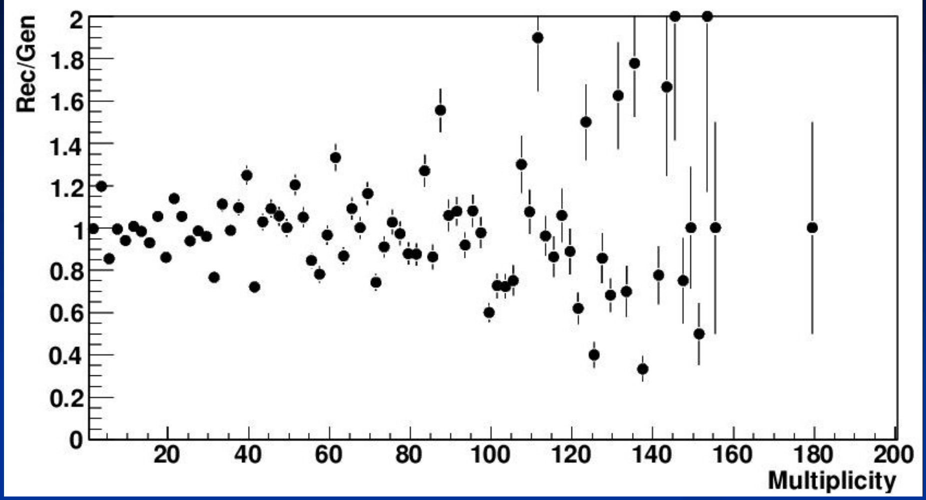


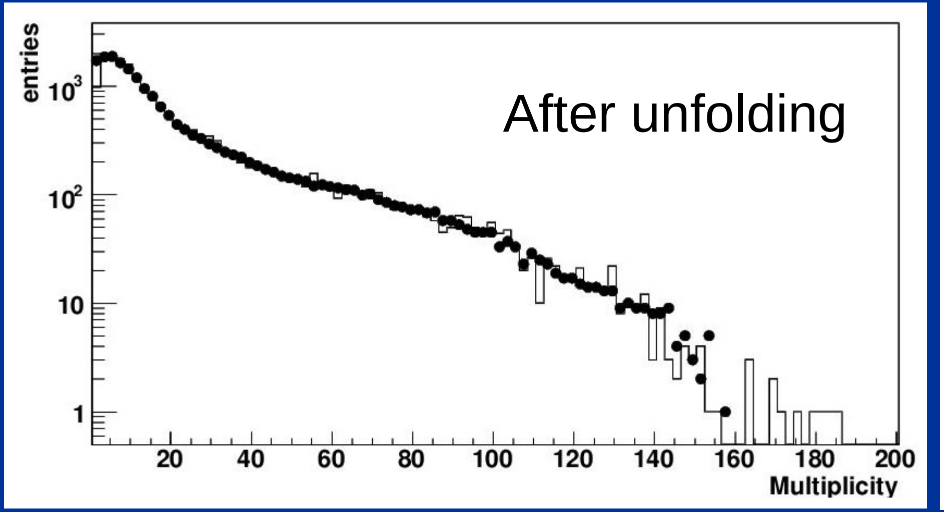
pp physics

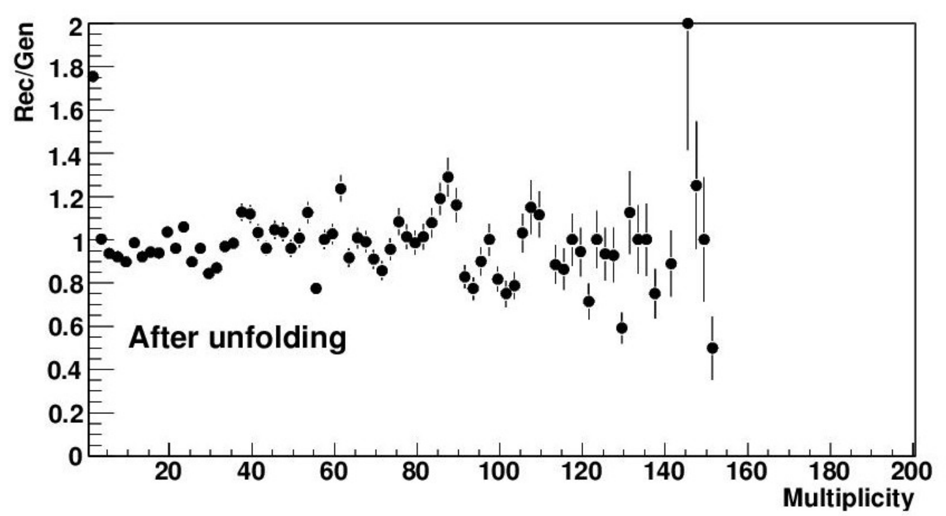
A few examples of the ALICE capabilities
with first day / first month p-p data
(most probably, at 10 TeV c.m. energy)

Example: multiplicity

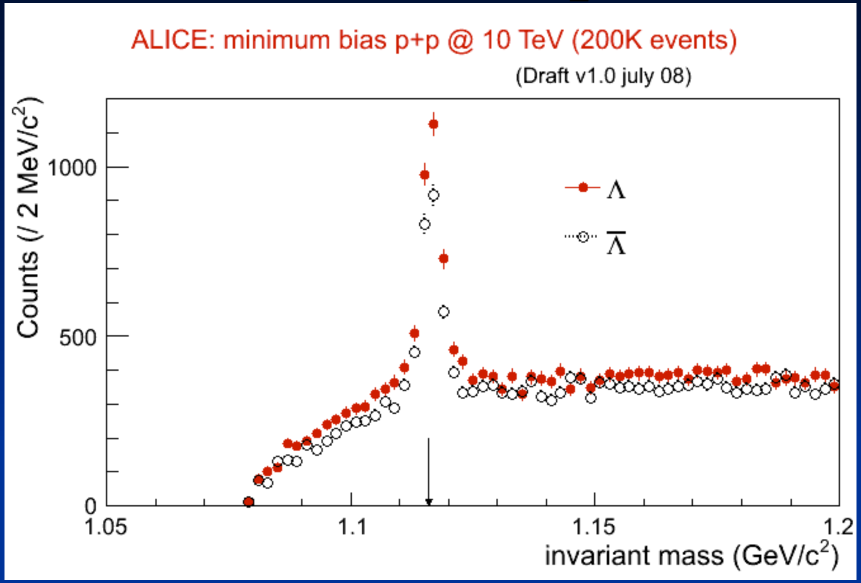


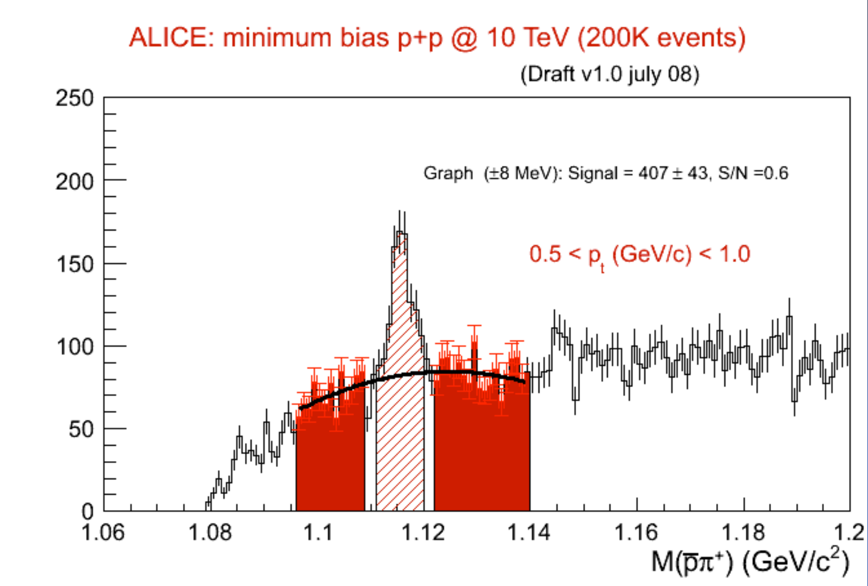


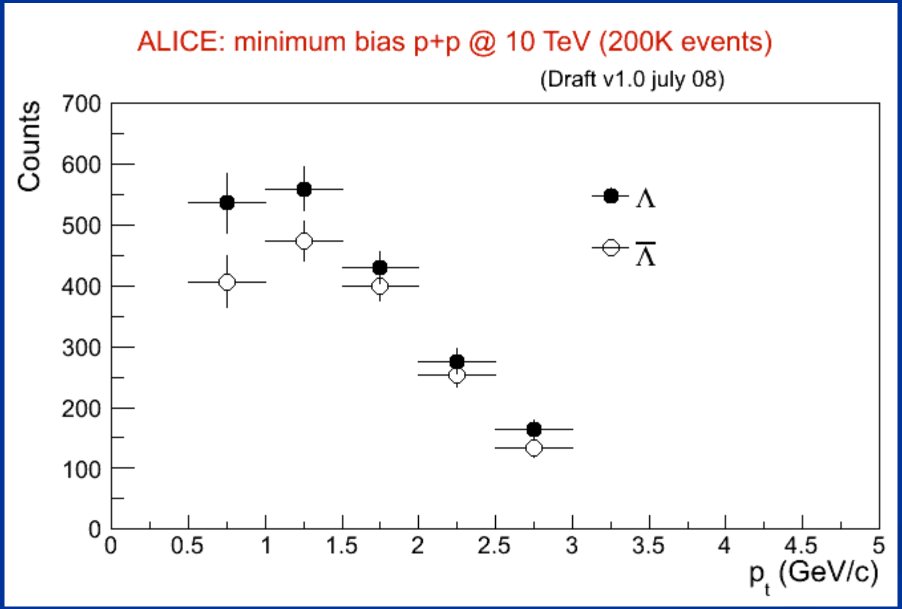




Example: Λ and anti-Λ

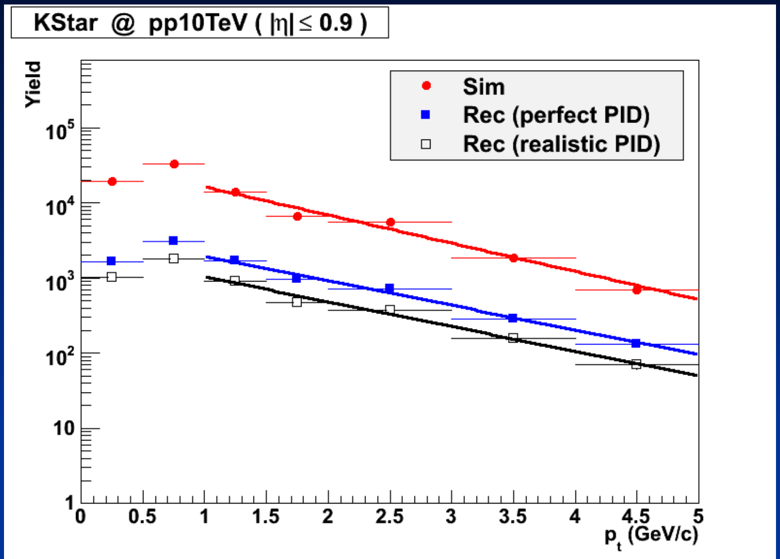


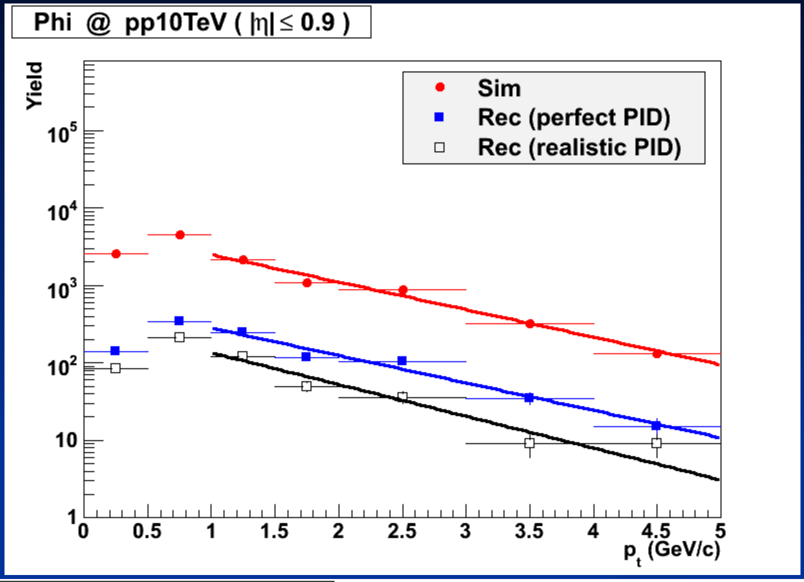




Tracking in ITS+TPC
Topological PID (decay vertex)
Gamma conversions partly removed
No correction for absorption

Example: Resonances

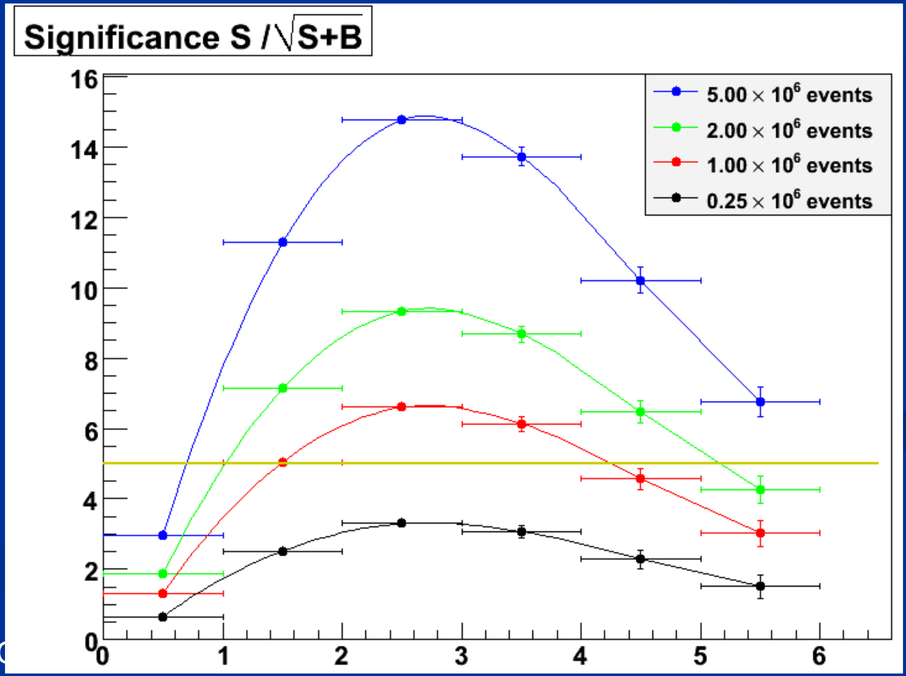




With 100K - a few 100K events:
with PID, ϕ and K* spectra feasible up to 3-4 GeV

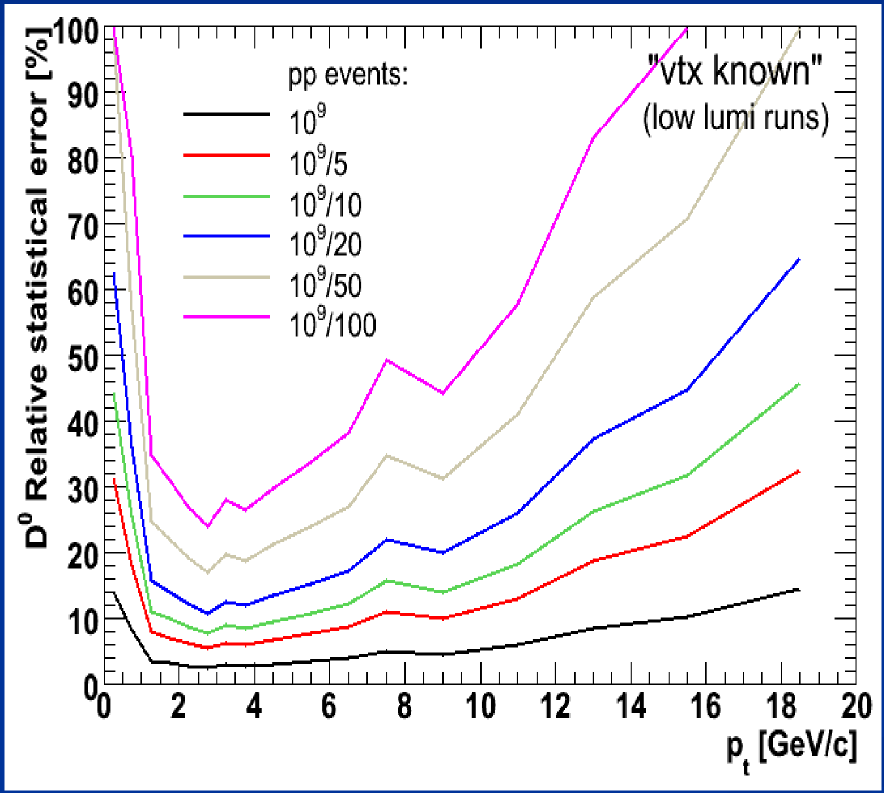
With 1M – a few M events:
ϕ reconstruction feasible without PID, being studied for K*

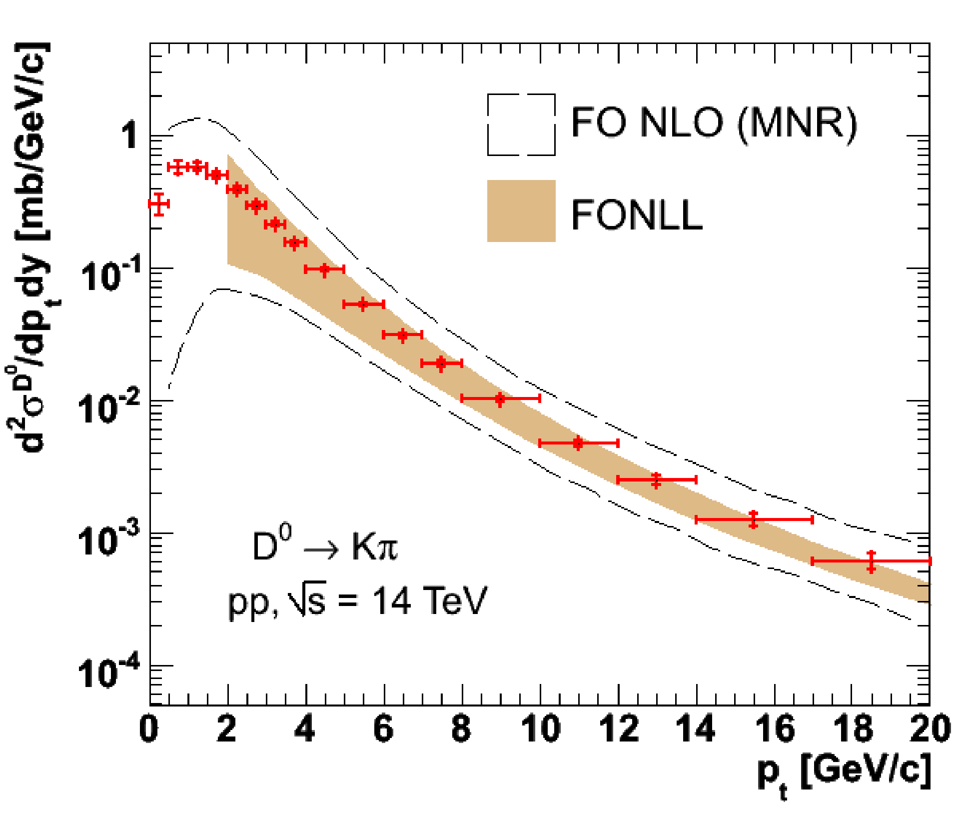
Example of “first day” ϕ analysis with TPC only, no PID
pp 10 TeV



Example: $D^0 \rightarrow K^- \pi^+$ in pp

- Expected statistical error
- Expected sensitivity in comparison to pQCD with 10^9 pp events





Conclusions

- ALICE detectors are installed, apart from full e.m. calorimetry (due for completion in 2011)
- All installed detectors are being commissioned with cosmic muons: calibration and alignment are well under way
- Analysis procedures have been developed and tested on the Grid, both for Pb-Pb and p-p first phyiscs
- We are looking forward to first p-p collisions in 2009

References

- ALICE Physics Performance Report:
  - Volume 1: F. Carminati et al., J. Phys. G. Nucl. Part. Phys. 30 (2004) 1517
  - Volume 2: B. Alessando et al., J. Phys. G. Nucl. Part. Phys. 32 (2006) 1295
- ALICE Detector technical paper:
  - K. Aamodt et al., The ALICE Experiment at the CERN LHC, 2008 JINST 3 S08002.
- http://aliceinfo.cern.ch/

Many thanks to…

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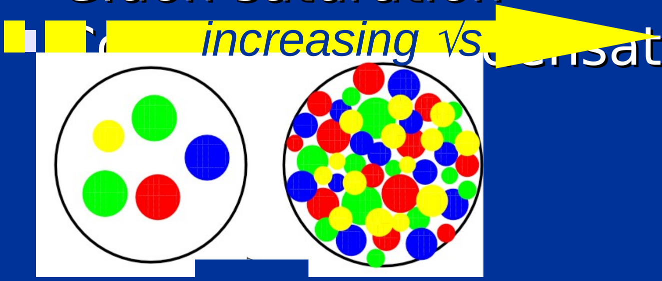
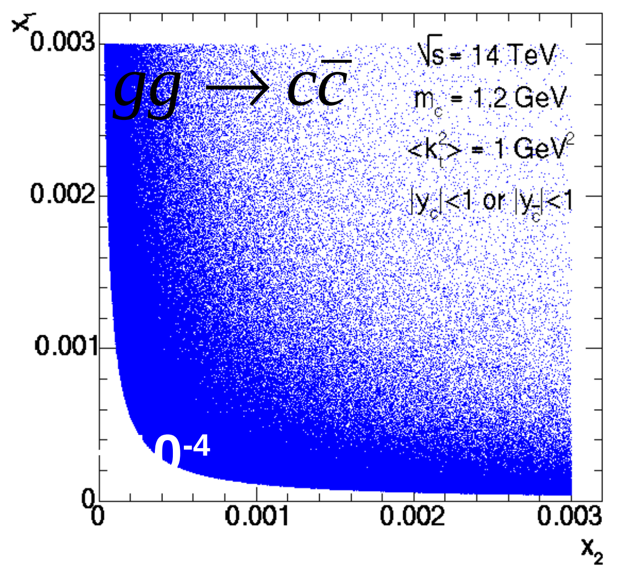
  - Bruno Alessandro
  - Angela Badalà
  - Boris Hippolyte
  - Christian Kuhn
  - Francesco Prino
  - Alberto Pulvirenti
  - Enrico Scomparin

Backup

Charm and Beauty at the LHC

- Small X
  - unexplored small-x region probed with charm at low pT and/or forward rapidity
    - down to $x \sim 10^{-4}$ with the charm already at y=0
  - Window on the rich phenomenology of high-density PDFs:
    - Shadowing
    - Gluon saturation
    - Color Glass Condensate





  - Large spread in predictions
    - need for pA collision