Opportunities arising from combined measurements at RHIC and LHC

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Monday, February 13, 2017

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Charge and Outline

- In the mid-term future, data from sPhenix and future measurements at LHC will allow for comparative studies of hard processes across an unprecedented wide range of $\sqrt{s}$. Which opportunities arise from that?

(1) Future Measurements at LHC
  - defined as post phase-I upgrade (past LS2)
  - ALICE, CMS, ATLAS, LHCb

(2) Future Measurement at RHIC (past BES-II)
  - sPHENIX, STAR

(3) Opportunities in comparative studies

LHC Plans

Run 2:

- 2017 - no heavy-ions
- 2018 - heavy-ion run in November

LS2 (2019/2020)

- Install phase-I upgrades, mostly ALICE & LHCb
- Only moderate upgrades to ATLAS and CMS

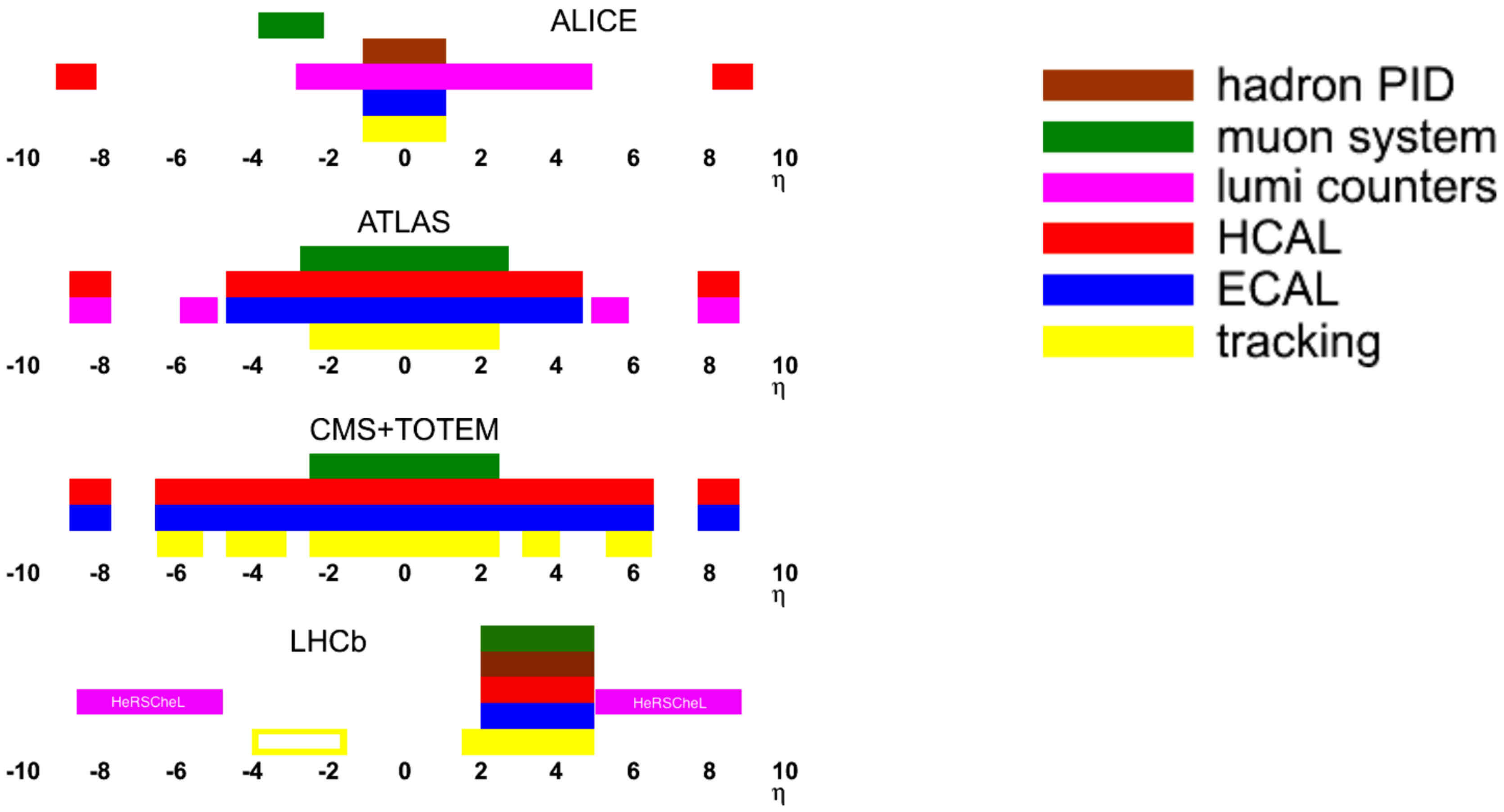
Run 3:

- Focus for our discussion

LS3 ($\gtrsim$2024):

- Phase-II upgrades of ATLAS and CMS focusing on High-Luminosity LHC
- Heavy-Ion plans not well defined for Run 4

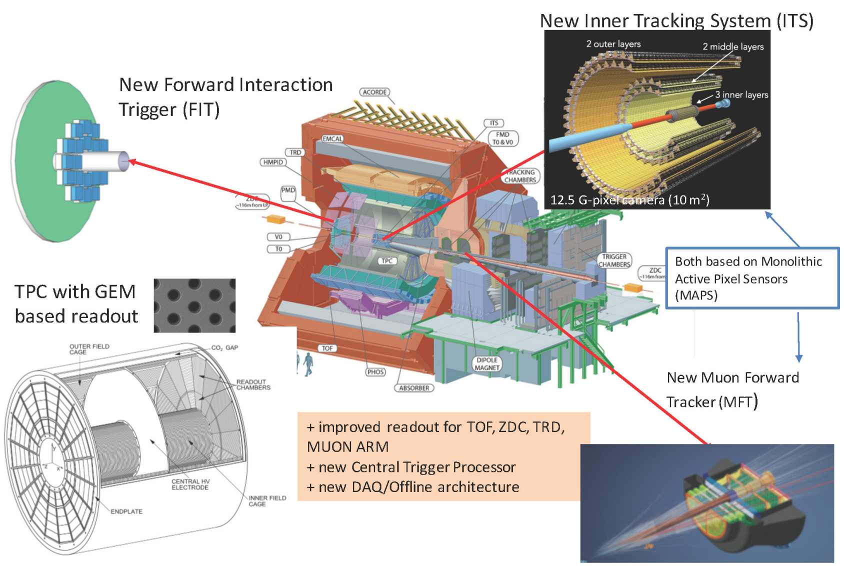
LHC - Experimental Coverage



ALICE Upgrades (I)

- ALICE's Intent
  - Studies following LS2 will focus on rare probes, and the study of their coupling with the medium and hadronization processes. These include heavy-flavour particles, quarkonium states, real and virtual photons, jets and their correlations with other probes
- Requirements
  - High statistics and high precision measurements are required
  - Many of these measurements will involve complex probes at low transverse momentum, where traditional methods for triggering will not be applicable.
- Strategy
  - After LS2, LHC will reach interaction rates of ~50 kHz
  - Upgrade the current detector by enhancing its low-p vertexing and tracking capability
  - Modify ALICE detector such that all interactions can be inspected accumulating 10 nb^{-1} of Pb–Pb collisions

ALICE Upgrades (II)



Electronic & Trigger

- Enable continuous (not triggered) readout to allow recording 50kHz

Online & Offline

- Real time analyses and filtering/compression of all events using massive computing resources

- TPC Upgrade
  - Ungated MWPC -> 4 GEM Readout
  - Retain current resolutions (p, dE/dx) but allow for higher rates
- New Inner Si Tracker
  - Considerable higher performance than current ITS
  - Higher resolution, higher speed, thin MAPS sensors
- New Forward Si Tracker
  - Augment muon detector performance

ALICE Physics Plans (I)

Central Barrel:

- Yields and azimuthal distributions of hadrons containing heavy quarks (c, b) to study the mechanism of heavy-quark thermalization in the QGP.
- Production of quarkonia at low p_T, in particular the study of their possible dissociation and regeneration mechanisms in the QGP.
- Low-mass dielectron production to extract information on early temperature and the partonic equation of state, and to characterize the chiral phase transition.
- Jets and jet correlations, in particular their structure and particle composition, to study the mechanism of partonic energy loss in medium and its dependence on parton color-charge, mass and energy.
- The production of nuclei, anti-nuclei and hyper-nuclei as well as exotic hadronic states such as the H-dibaryon.

ALICE Physics Plans (II)

Forward (MFT + Muon Arm):

- Evaluate the medium temperature and study charmonium dissociation and regeneration mechanisms via measurements of prompt J/psi and psi; production and elliptic flow;
- Pin down the medium equation of state and study the degree of thermalization of heavy quarks in the medium via measurements of heavy flavour and charmonium elliptic flow;
- Extract the energy density of the medium, the color charge and mass dependence of parton in-medium energy loss via measurements of
  - heavy quark production separately for charm and beauty in the single muon channel;
  - J/psi from b-hadrons decay.
- Investigate the chiral nature of the phase transition via measurements of low mass vector mesons.

ALICE Run 3 Physics (General)

Physics Reach:

Observable	Approved p_T^{Amin} (GeV/c)	Approved statistical uncertainty	Upgrade p_T^{Umin} (GeV/c)	Upgrade statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 % at p_T^{Amin}	0	0.3 % at p_T^{Amin}
D meson from B decays R_{AA}	3	30 % at p_T^{Amin}	2	1 % at p_T^{Amin}
D meson elliptic flow ($v_2 = 0.2$)	1	50 % at p_T^{Amin}	0	2.5 % at p_T^{Amin}
D from B elliptic flow ($v_2 = 0.1$)	not accessible		2	20 % at p_T^{Umin}
Charm baryon-to-meson ratio	not accessible		2	15 % at p_T^{Umin}
D_s meson R_{AA}	4	15 % at p_T^{Amin}	1	1 % at p_T^{Amin}
Charmonia				
J/ψ R_{AA} (forward rapidity)	0	1 % at 1 GeV/c	0	0.3 % at 1 GeV/c
J/ψ R_{AA} (mid-rapidity)	0	5 % at 1 GeV/c	0	0.5 % at 1 GeV/c
J/ψ elliptic flow ($v_2 = 0.1$)	0	15 % at 2 GeV/c	0	5 % at 2 GeV/c
ψ(2S) yield	0	30 %	0	10 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$)	not accessible			10 %
Low-mass spectral function	not accessible		0.3	20 %
Heavy Nuclear States				
Hyper(anti)nuclei $^4_\Lambda$H yield		35 %		3.5 %
Hyper(anti)nuclei $^4_{\Lambda\Lambda}$H yield	not accessible			20 %

ALICE Run 3 Physics (ITS)

Physics Reach:

Observable	Current, $0.1\,\mathrm{nb}^{-1}$		Upgrade, $10\,\mathrm{nb}^{-1}$	
	$p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	statistical uncertainty	$p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
$\mathrm{D_s}$ meson R_{AA}	4	15 %	< 2	3 %
D meson from B R_{AA}	3	30 %	2	1 %
J/ψ from B R_{AA}	1.5	15 % (p_{T}-int.)	1	5 %
B^+ yield	not accessible		3	10 %
Λ_{c} R_{AA}	not accessible		2	15 %
$\Lambda_{\mathrm{c}}/\mathrm{D}^0$ ratio	not accessible		2	15 %
Λ_{b} yield	not accessible		7	20 %
D meson v_2 ($v_2 = 0.2$)	1	10 %	0	0.2 %
$\mathrm{D_s}$ meson v_2 ($v_2 = 0.2$)	not accessible		< 2	8 %
D from B v_2 ($v_2 = 0.05$)	not accessible		2	8 %
J/ψ from B v_2 ($v_2 = 0.05$)	not accessible		1	60 %
Λ_{c} v_2 ($v_2 = 0.15$)	not accessible		3	20 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$) [4]	not accessible			10 %
Low-mass spectral function [4]	not accessible		0.3	20 %
Hypernuclei				
${}^{3}_{\Lambda}\mathrm{H}$ yield	2	18 %	2	1.7 %

ALICE Run 3 Physics (MFT+Muon Arm)

Physics Reach:

Observable	**p_T-coverage (GeV/c)**
Charm	
Prompt J/ψ – R_{AA} & v_2	$p_T(J/\psi) > 0$
$\psi(2S)$ – R_{AA}	$p_T(\psi') > 0$
μ from c-hadron decays – R_{AA} & v_2	$p_T(\mu) > 1$
Beauty	
Non-prompt J/ψ – R_{AA} & v_2	$p_T(J/\psi) > 0$
μ from b-hadron decays – R_{AA} & v_2	$p_T(\mu) > 3$
Chiral symmetry and QGP temperature	
Light vector mesons spectral functions and QGP thermal radiation	$p_T(\mu\mu) > 1$

ALICE Running

A *possible* running scenario for the operation of the upgraded ALICE detector could be the following:

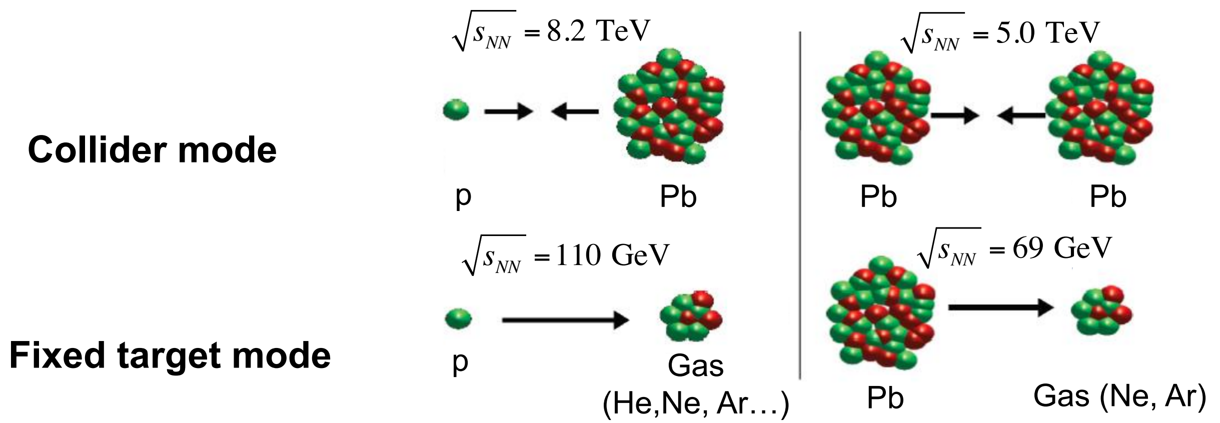
- 2019: Pb-Pb 2.85 nb^{-1}
- 2020: Pb-Pb 2.85 nb^{-1} at low magnetic field
- 2021: pp reference run
- 2022: LS3
- 2023: LS3
- 2024: Pb-Pb 2.85 nb^{-1}
- 2025: 50% Pb-Pb 1.42 nb^{-1} + 50% p-Pb 50 nb^{-1}
- 2026: Pb-Pb 2.85 nb^{-1}

LHCb Upgrades

- Intent
  - Focus on core pp program
  - Overcome limit of about few fb^{-1} of data per year
  - 1.1 MHz → 40 MHz
- Strategy
  - Replacing all the front-end electronics
  - New RICH detector
  - New VELO defector (Si tracking close to vertex)
  - Tracking: new, high-granularity silicon micro-strip planes and (behind the magnet) a Scintillating Fibre Tracker
- Heavy-Ions
  - Growing interest in nuclear beams, although small community
  - By now an active p-Pb program
  - First Pb-Pb running in 2015 up to semi-central collisions
  - Fixed target mode: p-Gas and Pb-Gas
  - Upgrades improved Pb–Pb centrality reach

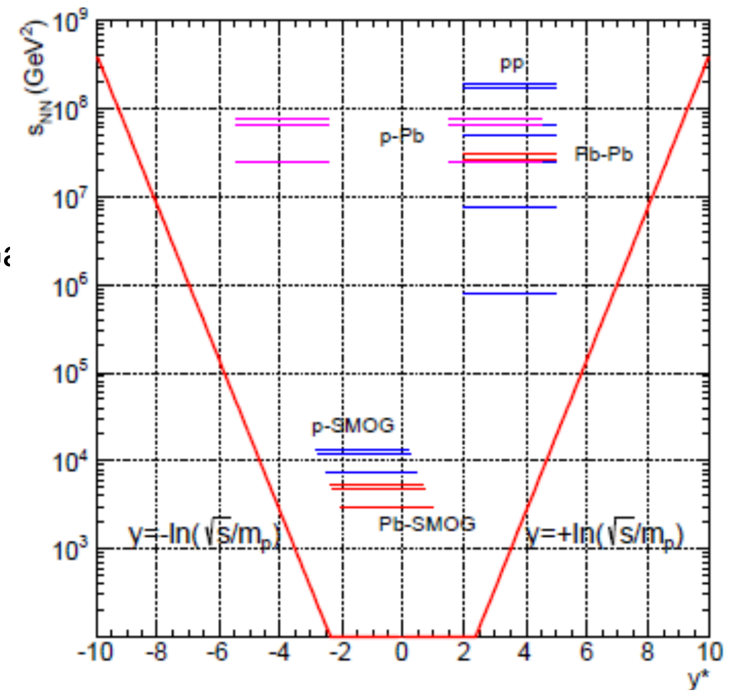
LHCb Kinematic and Reach

- Can operate in parallel collider and fixed target mode



- Kinematic acceptance

pp and p-Gas
pPb and Pbp
PbPb and Pb-Ga



- SPS/RHIC/LHC in one experiment

ATLAS Upgrades

- Intent
    - Improvements to cope with luminosities beyond the LHC nominal design value, while retaining the same physics performance.
    - Phase-I upgrades will allow ATLAS to maintain low p_T trigger thresholds
    - New set of very far forward detectors to explore diffractive physics
- Heavy-Ions
    - Program will benefit from improved all silicon tracker, higher granularity triggering on jets/electrons/photons, track triggers, topology triggers, improved muon tracker esp. in forward region, upgraded ZDC)

ATLAS in Run 3

- ATLAS (and CMS) can make full use of luminosity and improve on statistics hungry processes and increase p_T reach
  - Jet suppression, nPDF effects on W/Z/γ
  - γ+jet and Z+jet are very interesting channels and are also always statistics-limited.
  - Some important UPC channels (e.g. light-by-light scattering)
- Light ions are of particular interest but little interest from other experiments (so far).
  - Preference would be Ar+Ar, which would be of use to soft physics program (changing geometric fluctuations)

Backup Slides

ALICE - Open Charm (I)

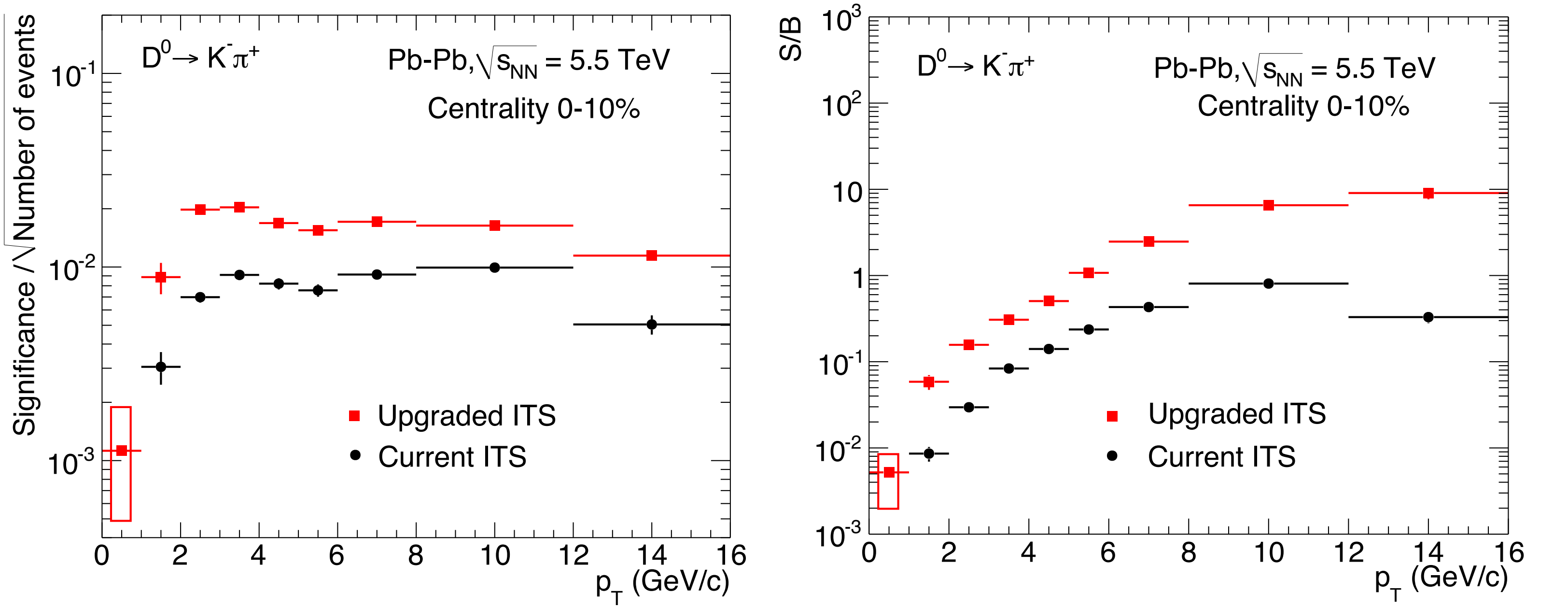


Figure 8.2: $D^0 \rightarrow K^-\pi^+$: comparison of the significance (left) and signal-to-background ratio (right) obtained for the current and upgraded ITS. The box indicates the systematic uncertainty of the estimate for the interval $0 < p_T < 1\,\mathrm{GeV}/c$.

ALICE - Open Charm (II)

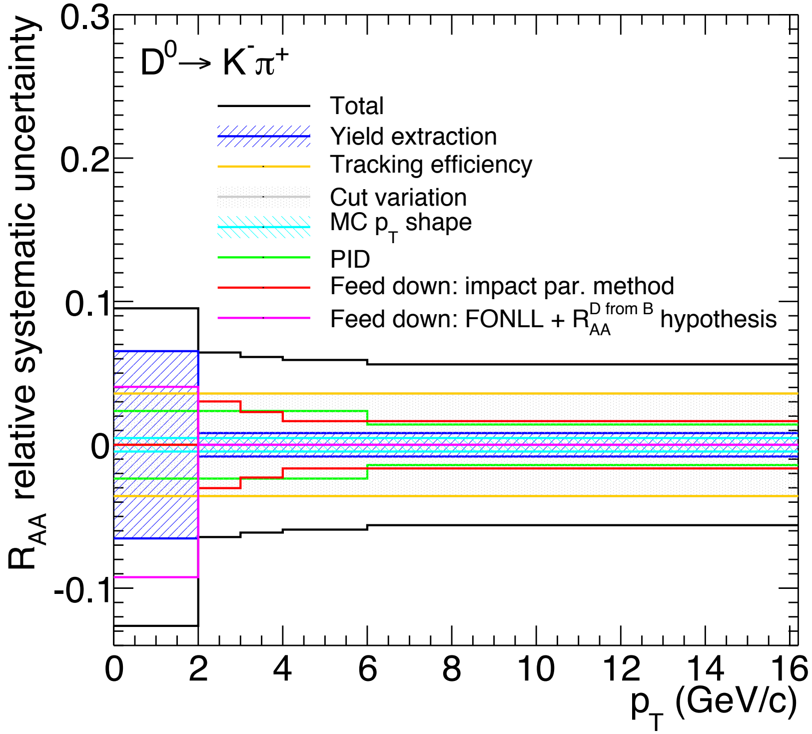


Figure 8.3: Relative systematic uncertainties on R_{AA} of prompt D^0 mesons.

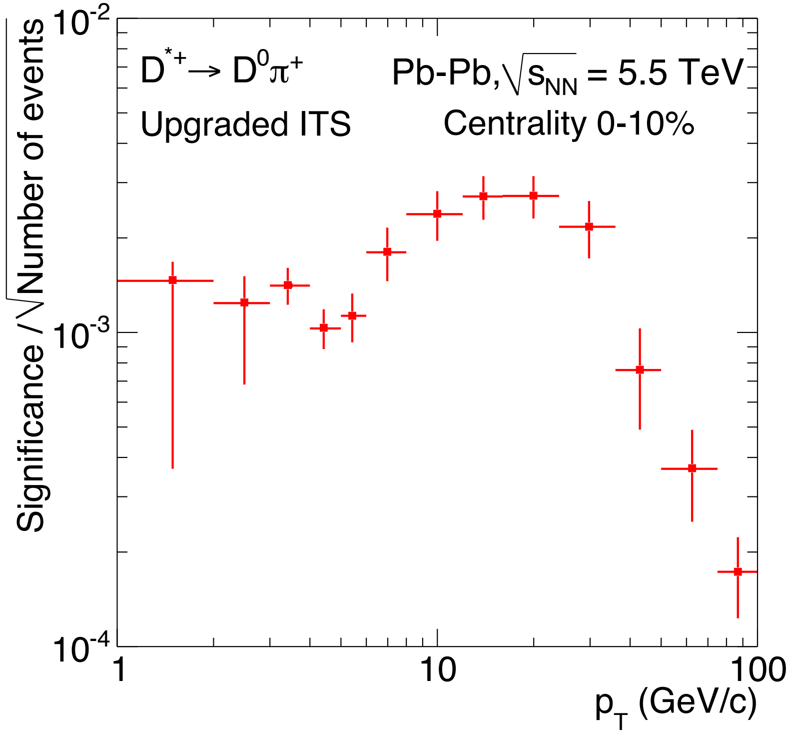


Figure 8.4: D^{*+} statistical significance, normalized to one event, for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV in the centrality class 0–10 %, with the upgraded ITS.

ALICE - Open Charm (III)

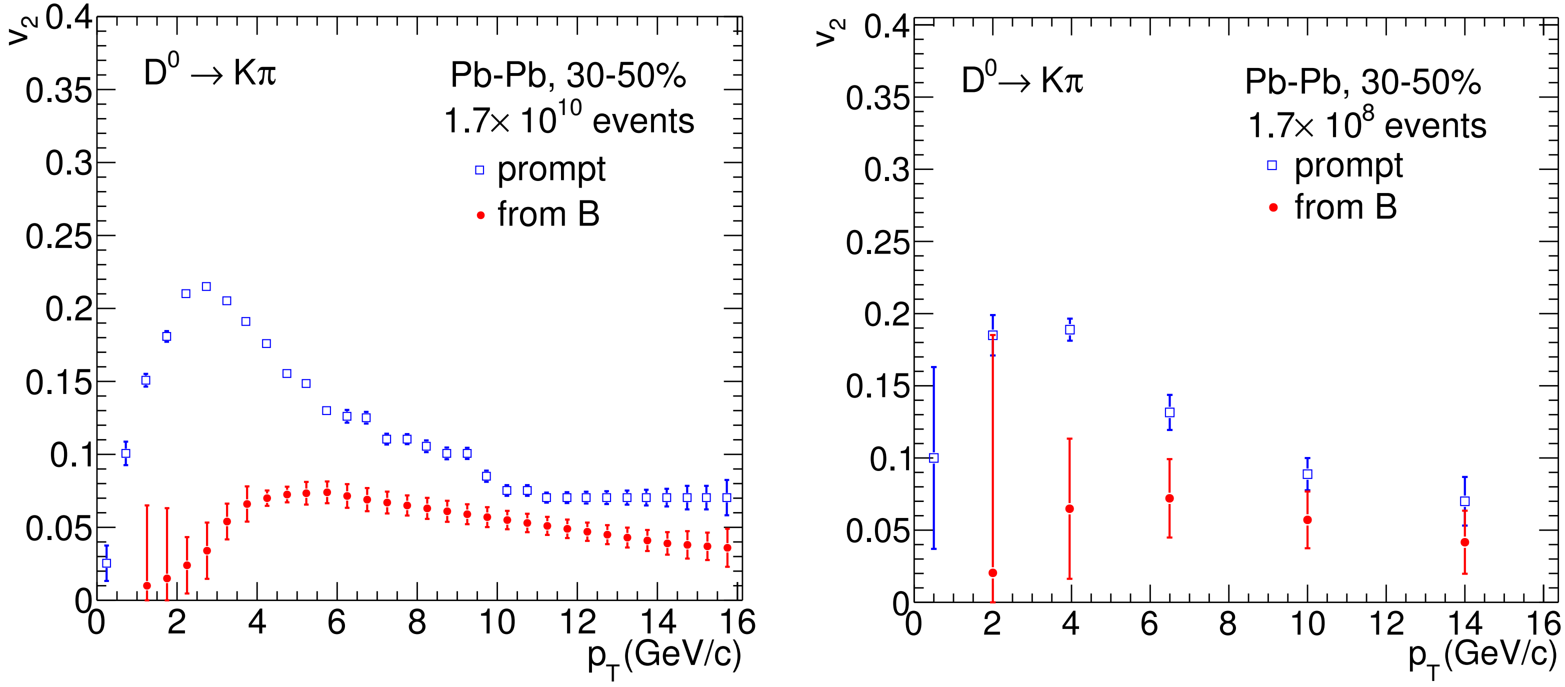


Figure 2.20: Estimated statistical uncertainties on v_2 of prompt and secondary D^0 mesons for $1.7 \cdot 10^{10}$ events (left) in the 30–50% centrality class, which correspond to 10 nb^{-1}, and for $1.7 \cdot 10^8$ events (right), which correspond to about 0.1 nb^{-1}.

ALICE - Open Charm (IV)

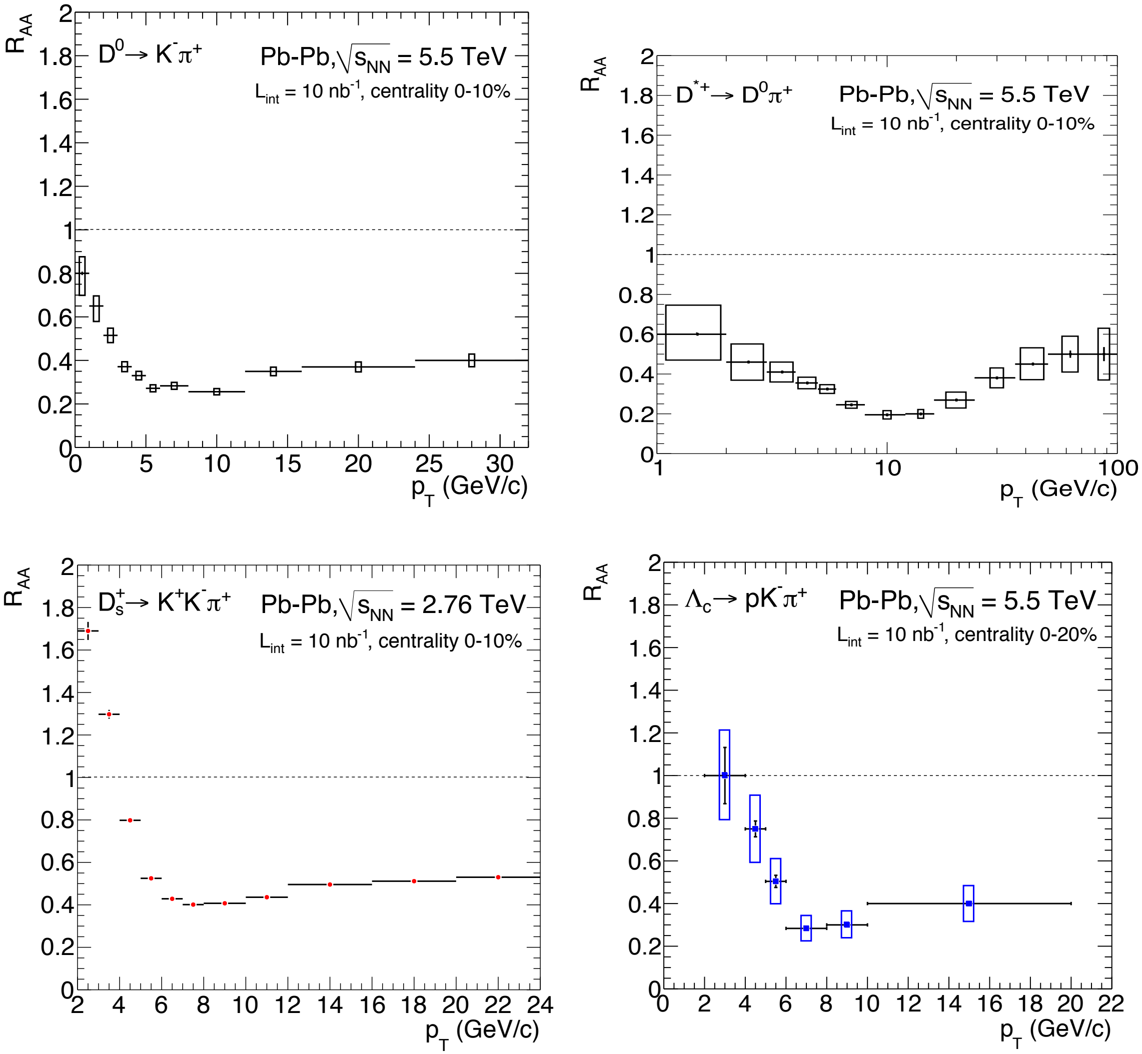


Figure 8.18: Nuclear modification factor of D^0 (top-left), D^{*+} (top-right), D_s^+ (bottom-left, only statistical uncertainties) and Λ_c^+ (bottom-right) for central Pb–Pb collisions ($L_{int} = 10\,nb^{-1}$).

ALICE - Open Charm (V)

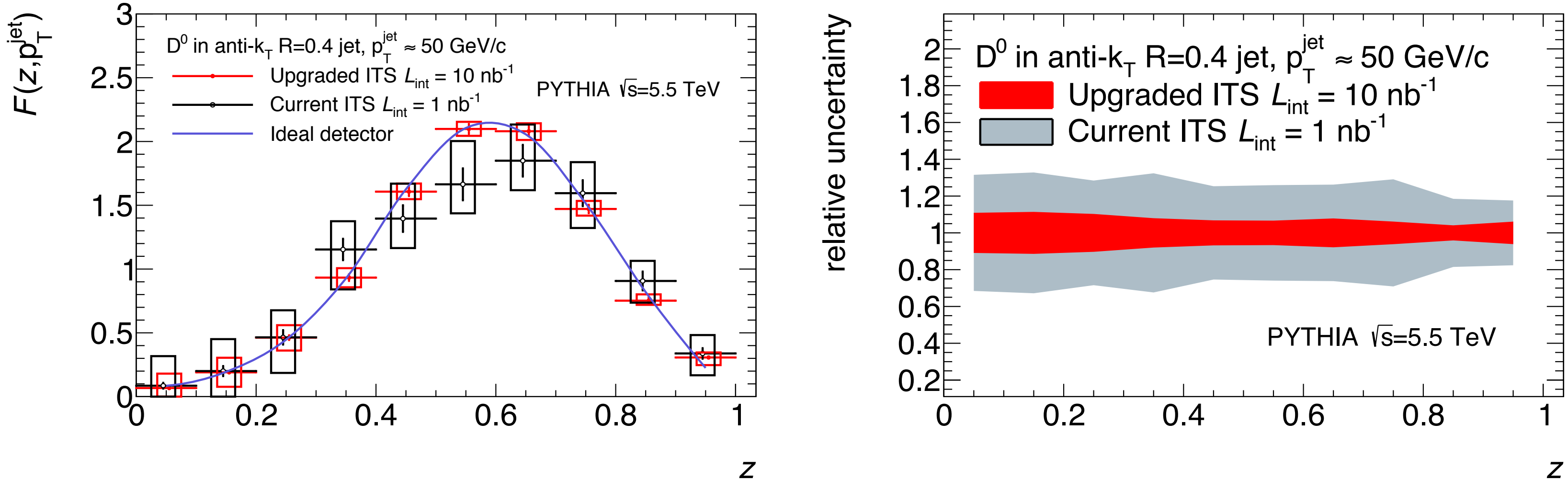


Figure 8.22: Projected D-jet fragmentation z distribution for 50 GeV/c c quark jets in central (0–10 %) Pb–Pb collisions for the current detector for 1 nb^{-1} and upgraded detector for 10 nb^{-1} (left). Comparison of the total uncertainties (systematic and statistical added in quadrature) for the two cases (right).

ALICE - Charm Baryons (I)

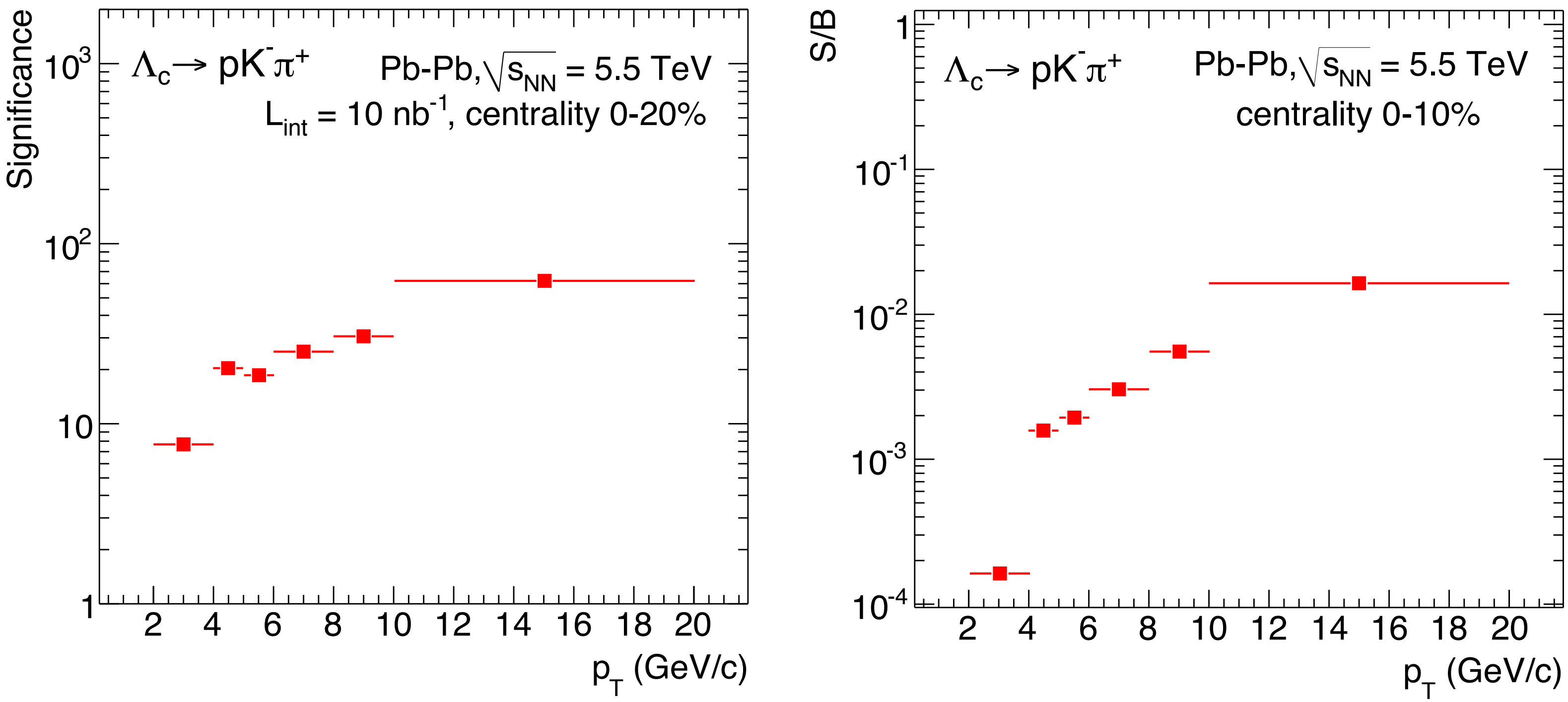


Figure 8.14: $\Lambda_c \rightarrow \mathrm{pK}\pi$ in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$: significance (left) and S/B ratio (right) as a function of p_{T}. The significance is scaled to 1.6×10^{10} events, which correspond to the statistics in the centrality class 0–20 % for $L_{\mathrm{int}} = 10\,\mathrm{nb}^{-1}$.

ALICE - Charm Baryons (II)

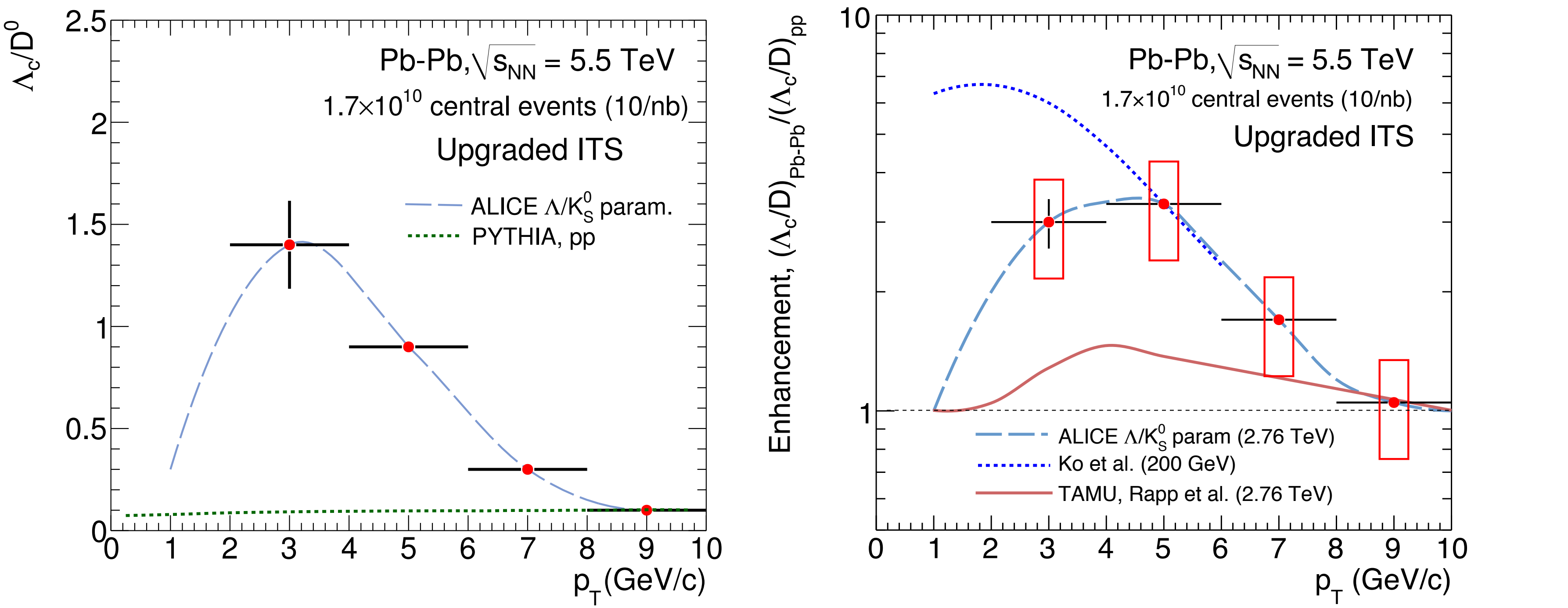


Figure 2.19: Left: estimated statistical uncertainties on the measurement of the Λ_c/D^0 ratio using 1.7×10^{10} central Pb–Pb collisions (0–20%), corresponding to an integrated luminosity of 10 nb^{-1}. The points are drawn on a line that captures the trend and magnitude of the Λ/K^0_S ratio (see Figure 2.4). The pp expectation from the PYTHIA 6.4.21 generator [46] is also shown. Right: enhancement of the Λ_c/D ratio in central Pb–Pb with respect to pp collisions. Two model calculations [24, 27] are also shown.

ALICE - Beauty (I)

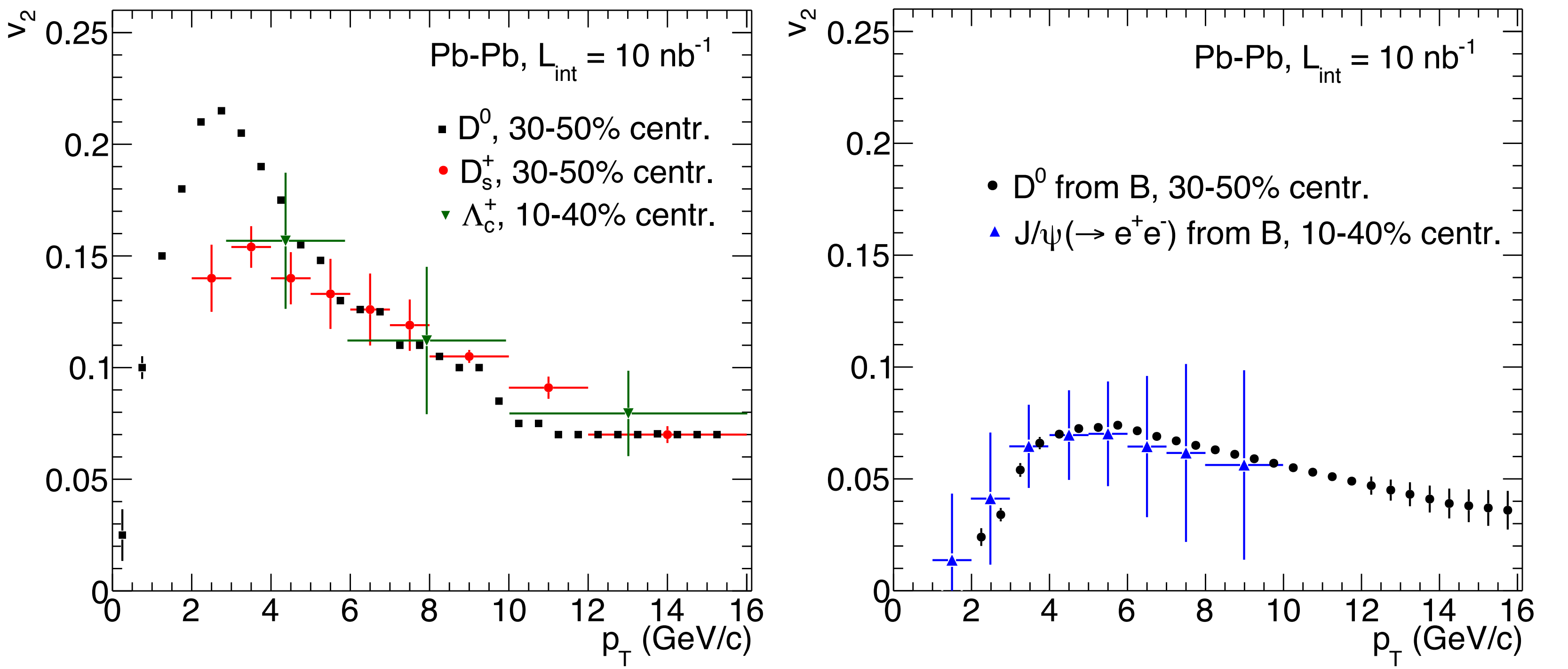


Figure 8.21: v_2 of D^0, D_s^+ and Λ_c (left) and of D^0 and J/ψ from B decays (right) with estimated statistical uncertainties for $L_\mathrm{int} = 10\,\mathrm{nb}^{-1}$.

ALICE - Beauty (II)

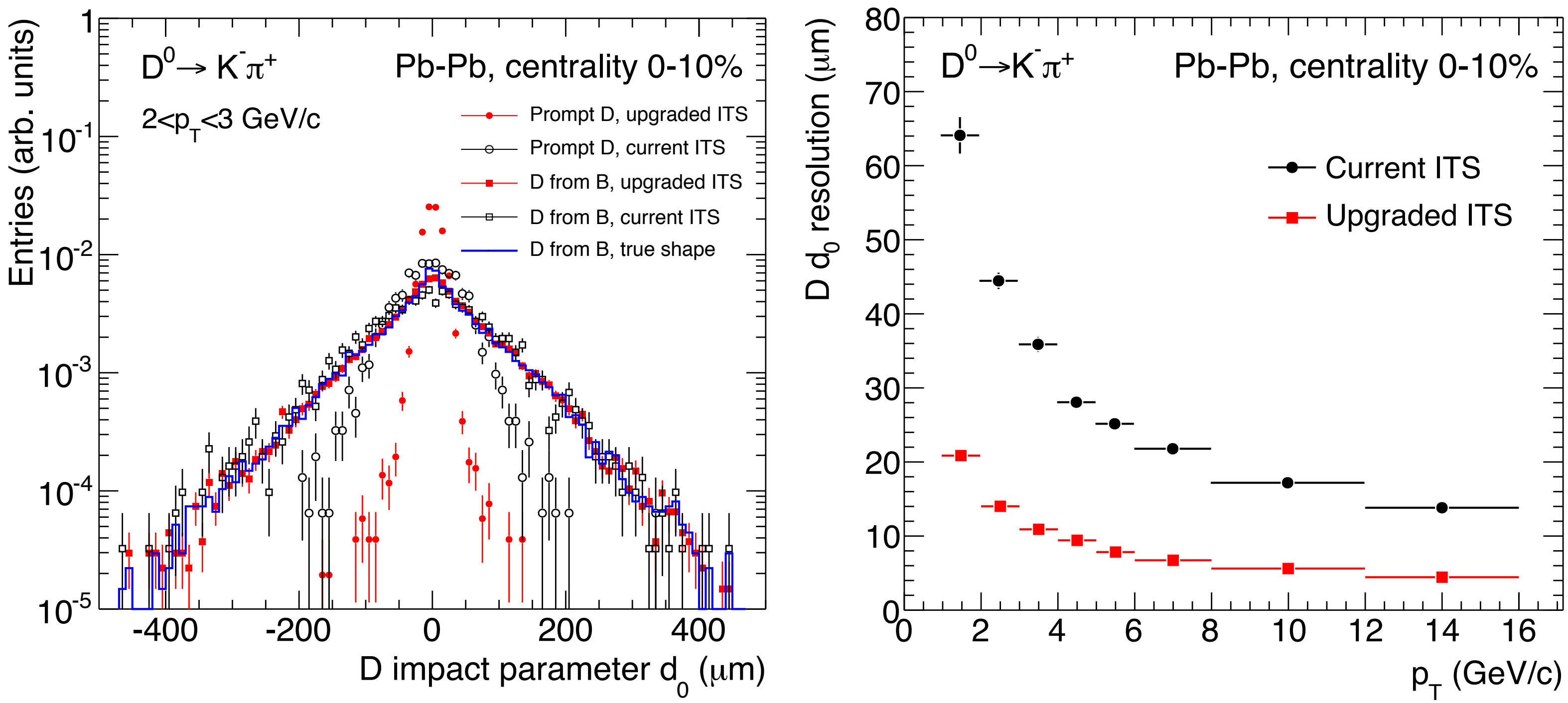


Figure 8.6: Impact parameter distributions for prompt and secondary (from B decays) D^0 obtained with the current and upgraded ITS configurations in the interval $2 < p_T < 3\,\mathrm{GeV}/c$ (left). Impact parameter resolution as a function of p_T (right).

ALICE - Beauty (III)

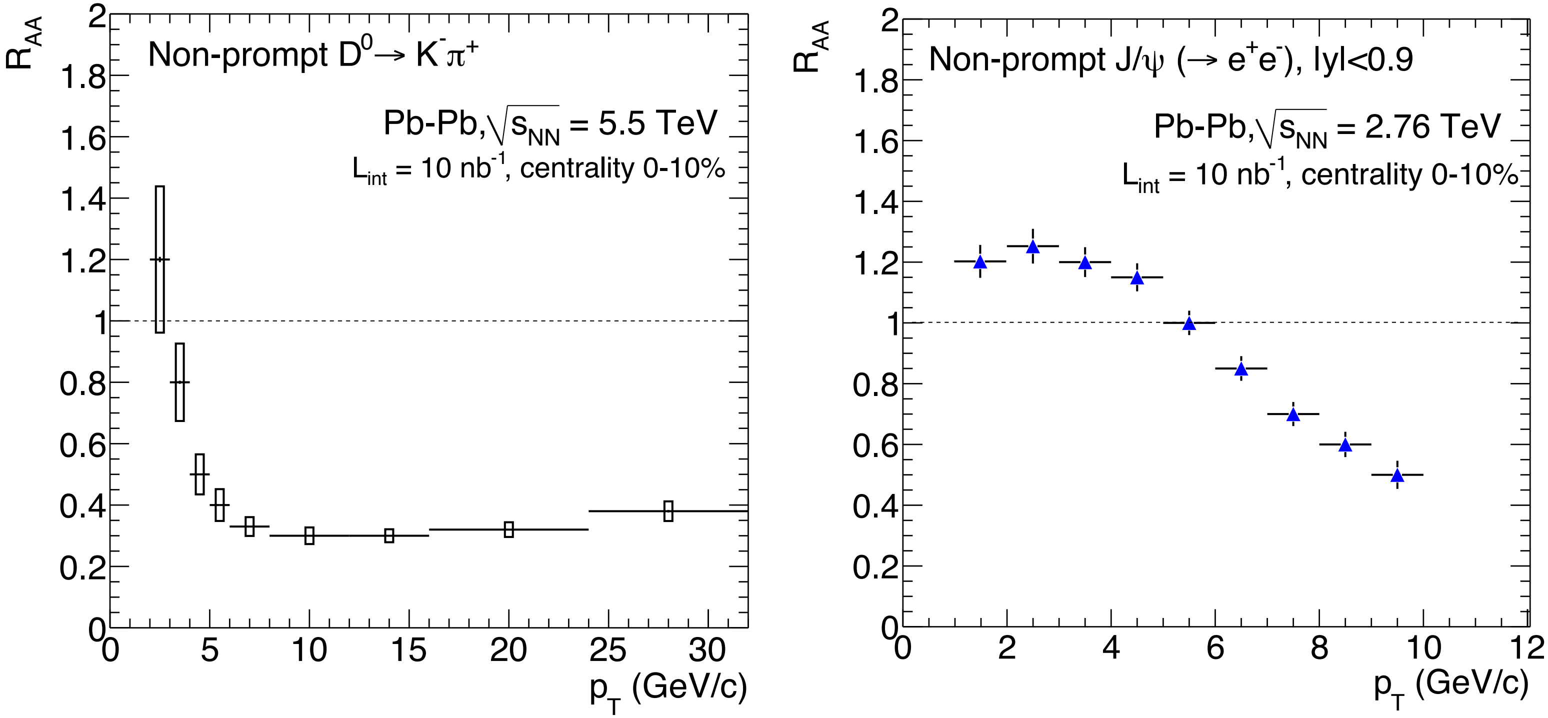


Figure 8.19: Nuclear modification factor of D^0 from B decays (left) and J/ψ from B decays (right, only statistical uncertainties) for central Pb–Pb collisions ($L_{\mathrm{int}} = 10\,\mathrm{nb}^{-1}$).

ALICE - Beauty (IV)

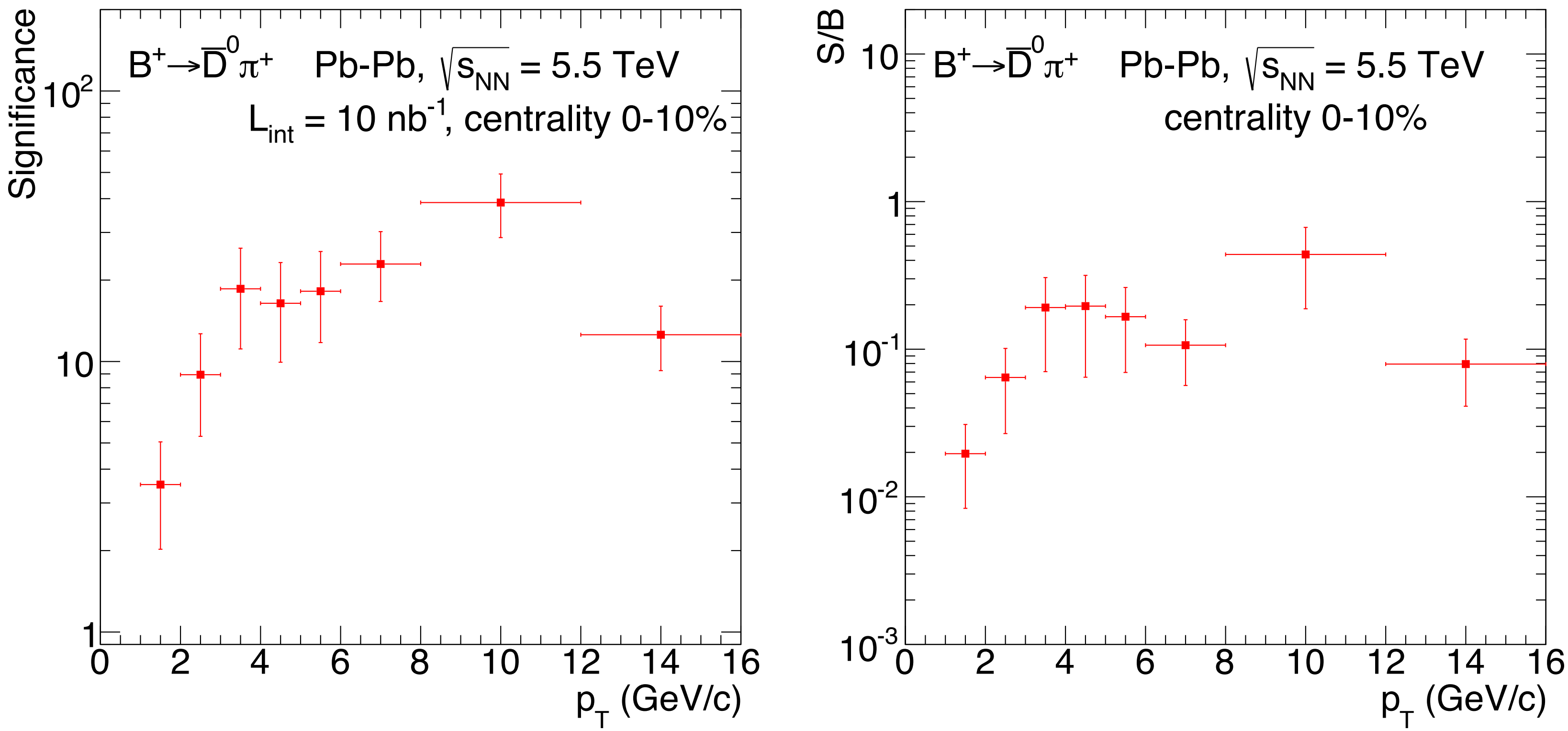


Figure 8.13: $B^+ \to \overline{D}^0\pi^+$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$: the significance (left) is scaled to 8×10^9 events for 0–10 % centrality, corresponding to $L_{\mathrm{int}} = 10\ \mathrm{nb}^{-1}$. The signal-to-background ratio is shown on the right.

ALICE - Beauty (V)

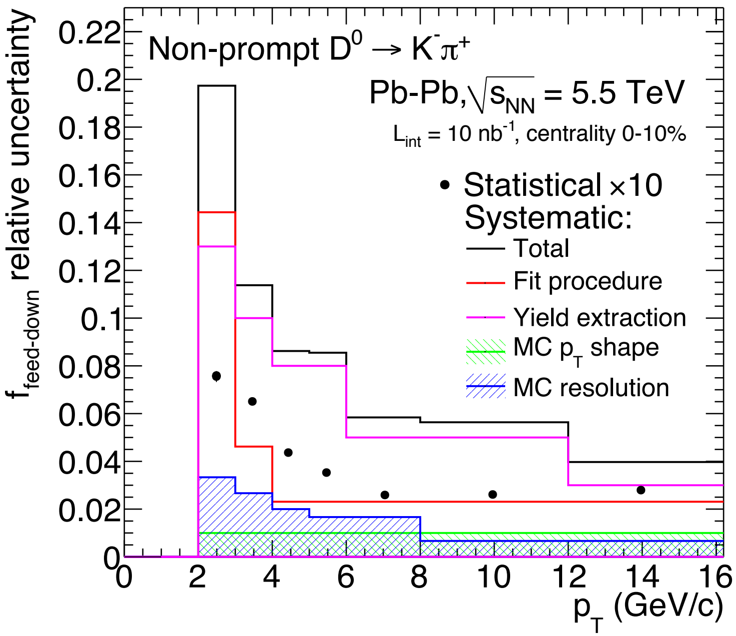


Figure 8.7: Relative statistical and systematic uncertainties on the fraction $f_{\text{feed-down}}$ of D^0 mesons from B decays, with the upgraded ITS in the centrality class 0–10 % for $L_{\text{int}} = 10\ \text{nb}^{-1}$. The statistical uncertainty is multiplied by 10 for better visibility.

ALICE - Beauty Baryons

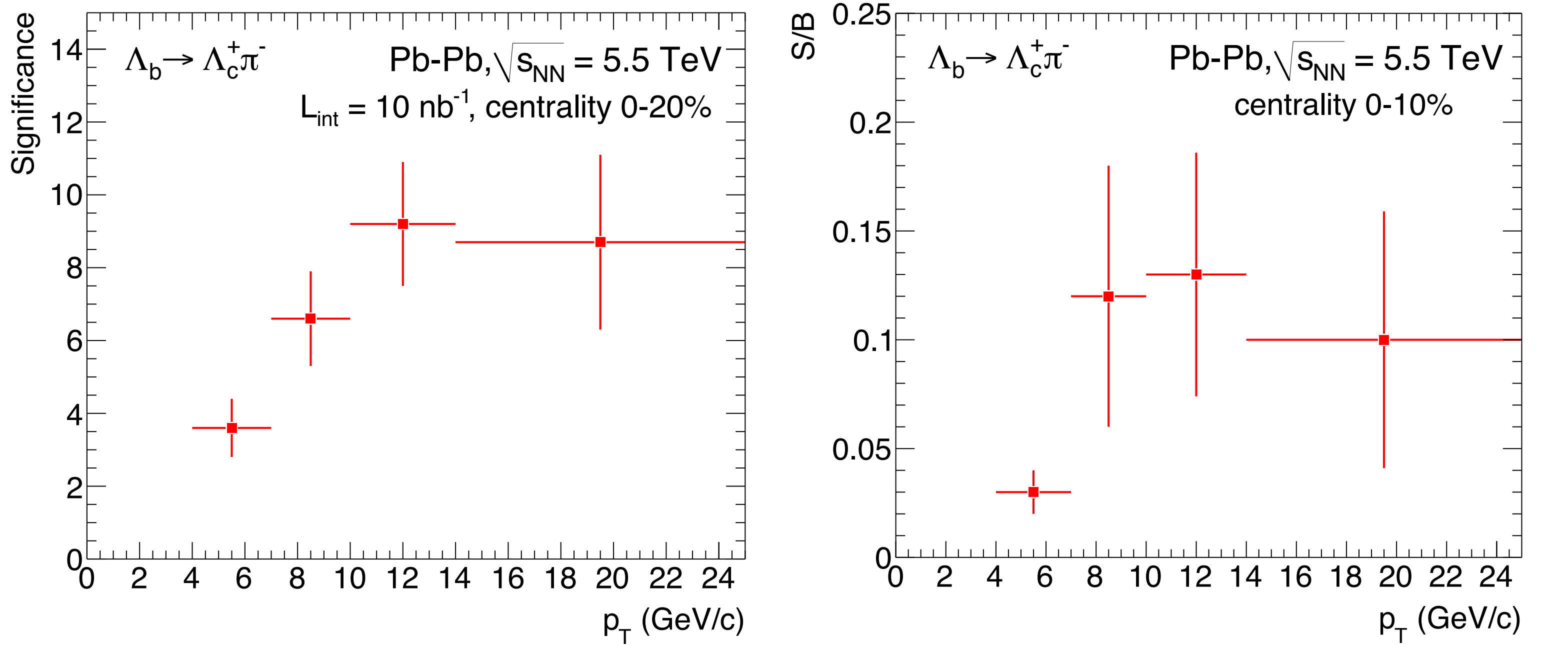


Figure 8.17: $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5\,\text{TeV}$: significance for $L_{int} = 10\,\text{nb}^{-1}$ (left) and S/B ratio (right) as a function of p_T.

ALICE - Quarkonia (I)

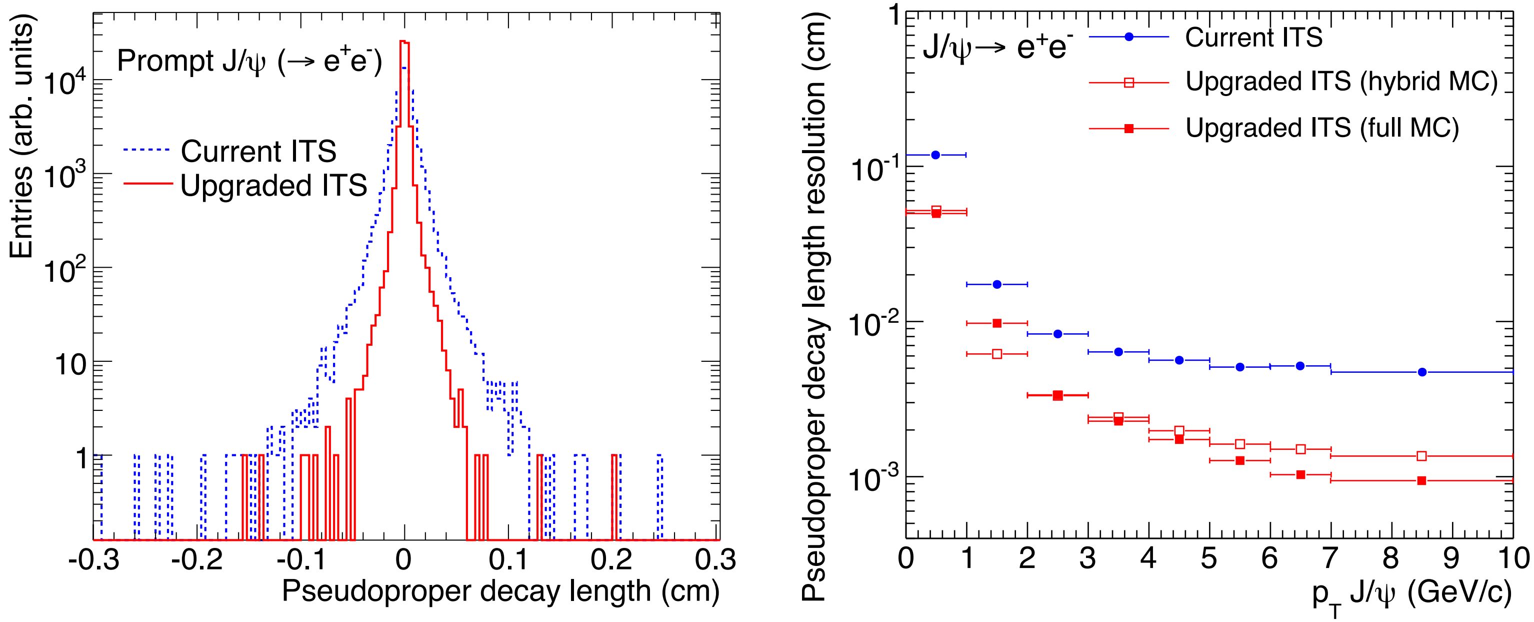


Figure 8.8: Left: Pseudo-proper decay length distribution for prompt J/ψ for the current and new ITS (*Hybrid* method). Right: Resolution as a function of p_T for the current and new ITS (*Hybrid* and full simulation).

ALICE - Quarkonia (II)

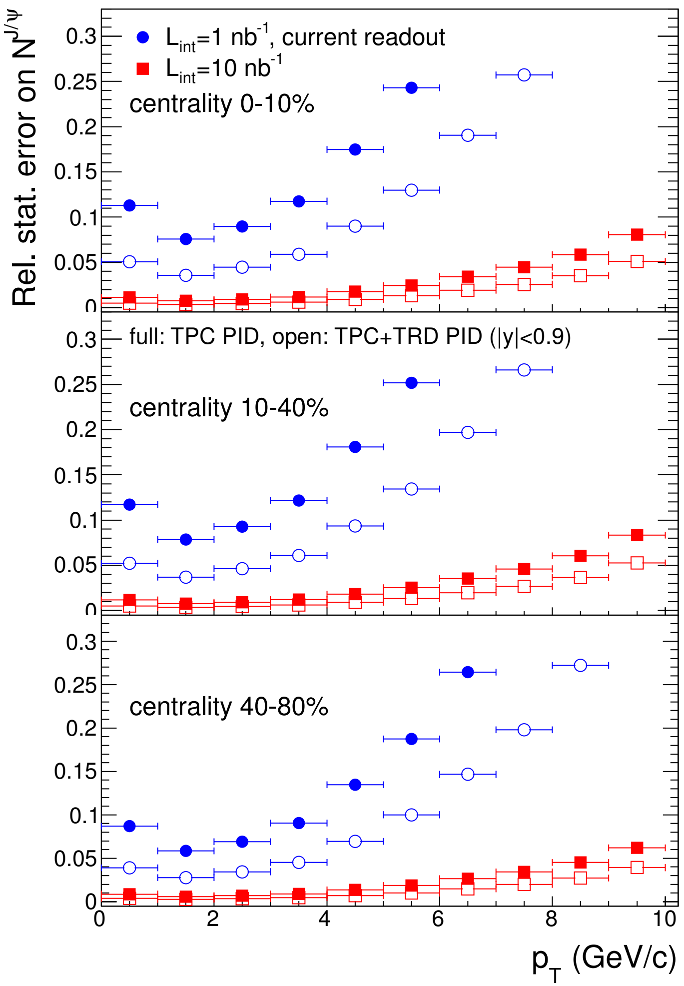


Figure 2.37: The statistical accuracy of the J/ψ yield measurement in the Central Barrel as a function of transverse momentum for three centrality classes. The full symbols are for electron identification employing only the TPC, the open ones for including also TRD.

ALICE - Quarkonia (III)

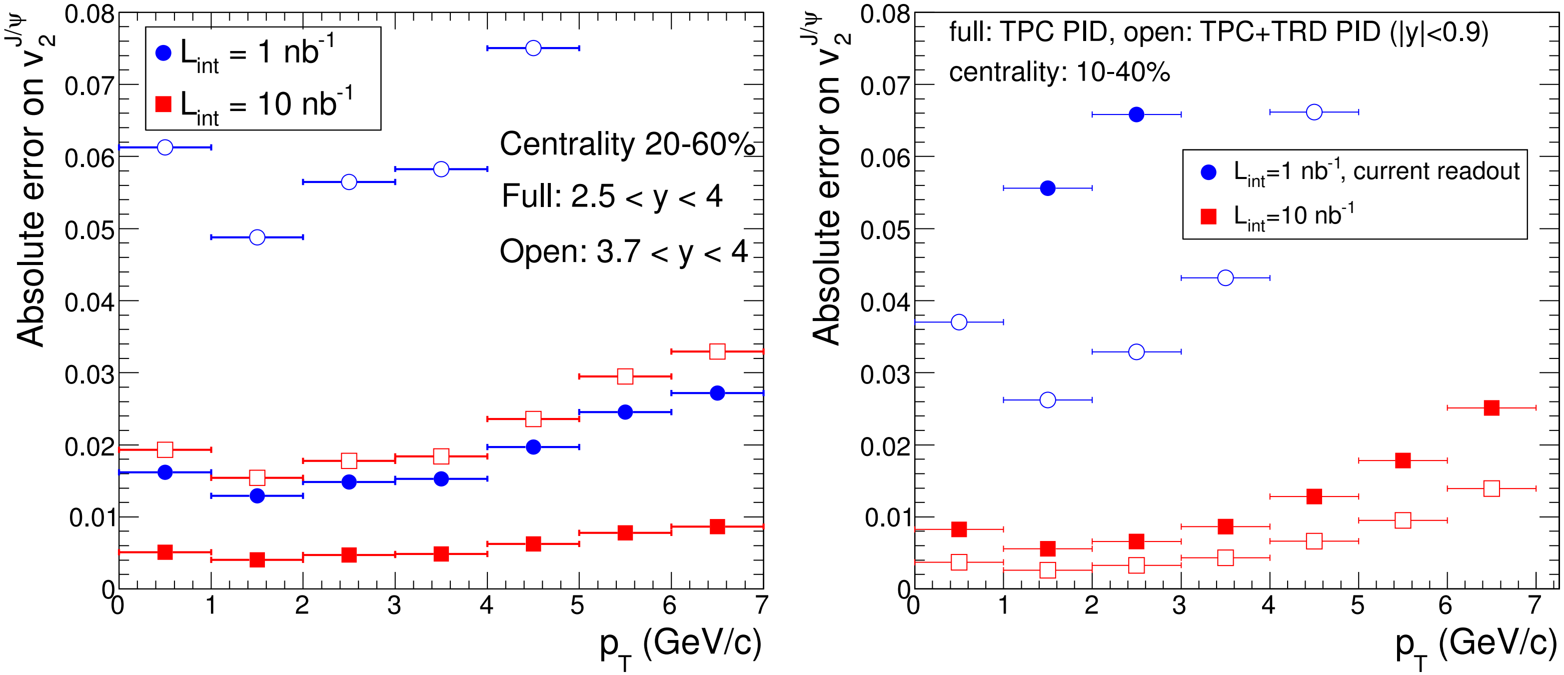


Figure 2.38: The absolute statistical error of the elliptic flow of J/ψ as a function of transverse momentum for the measurement with the Muon Spectrometer (left panel, centrality range 20-60%) and for the Central Barrel (right panel, centrality range 10-40%).

ALICE - Quarkonia (IV)

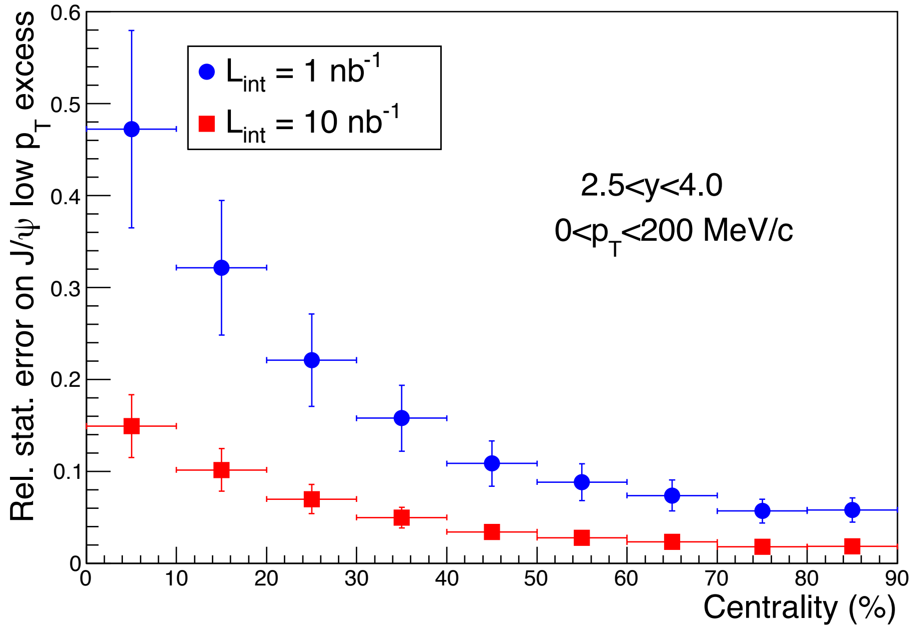


Figure 2.41: Centrality dependence of the relative statistical error of the low p_T J/ψ yield excess measured in Pb-Pb collisions at LHC energies.

ALICE - Quarkonia (V)

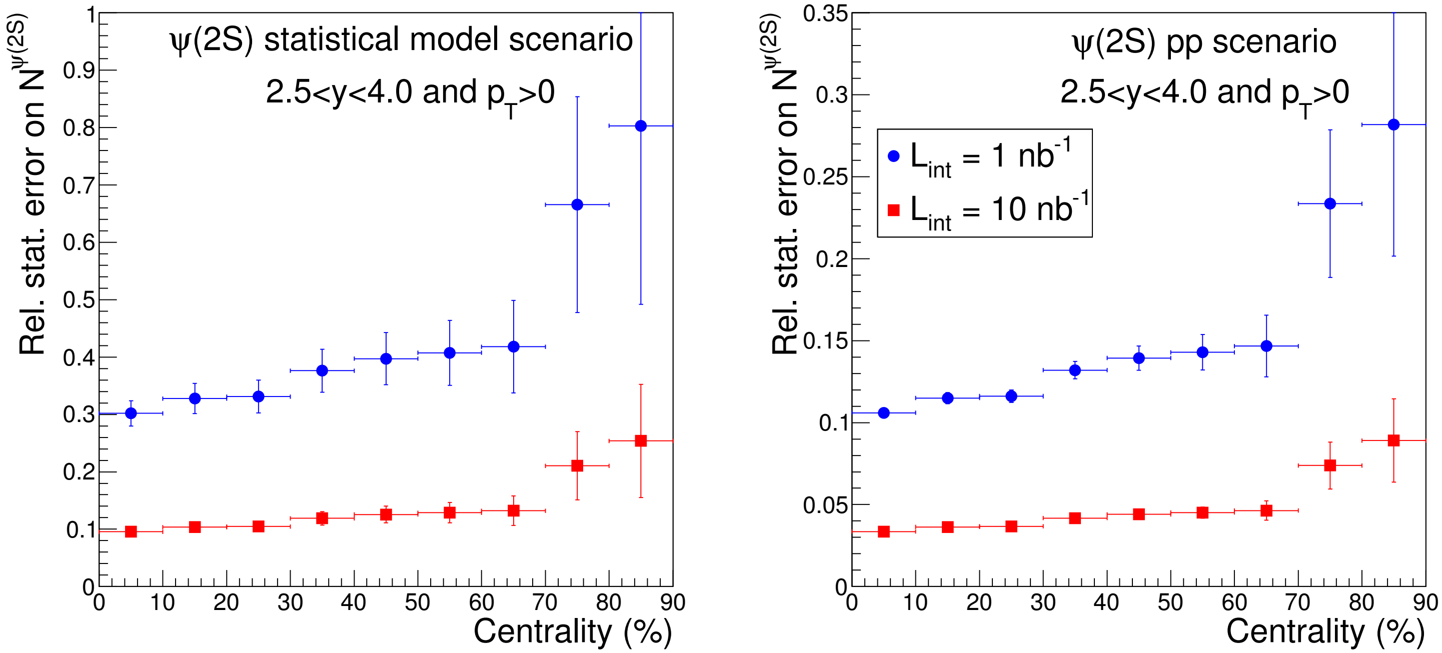


Figure 2.42: The estimated relative statistical error of the $\psi(2S)$ measurement in the Muon Spectrometer as a function of centrality for an integrated luminosity of 1 nb^{-1} and 10 nb^{-1}. Two scenarios are considered: the statistical model prediction (left panel) pp scaling (right panel).

ALICE - Quarkonia (VI)

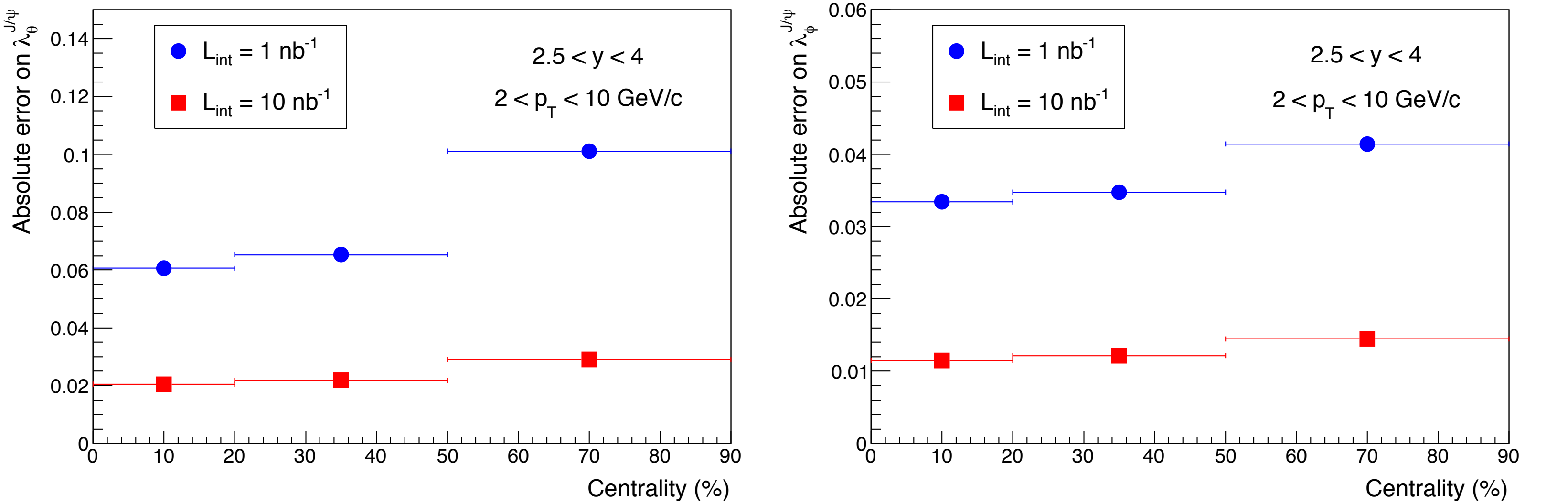


Figure 2.39: Absolute statistical error of the J/ψ polarization parameters λ_θ (left panel) and λ_ϕ (right panel) as a function of centrality, measured with the Muon Spectrometer for 1 nb^{-1} and 10 nb^{-1}.

ALICE - Jets and Photons (I)

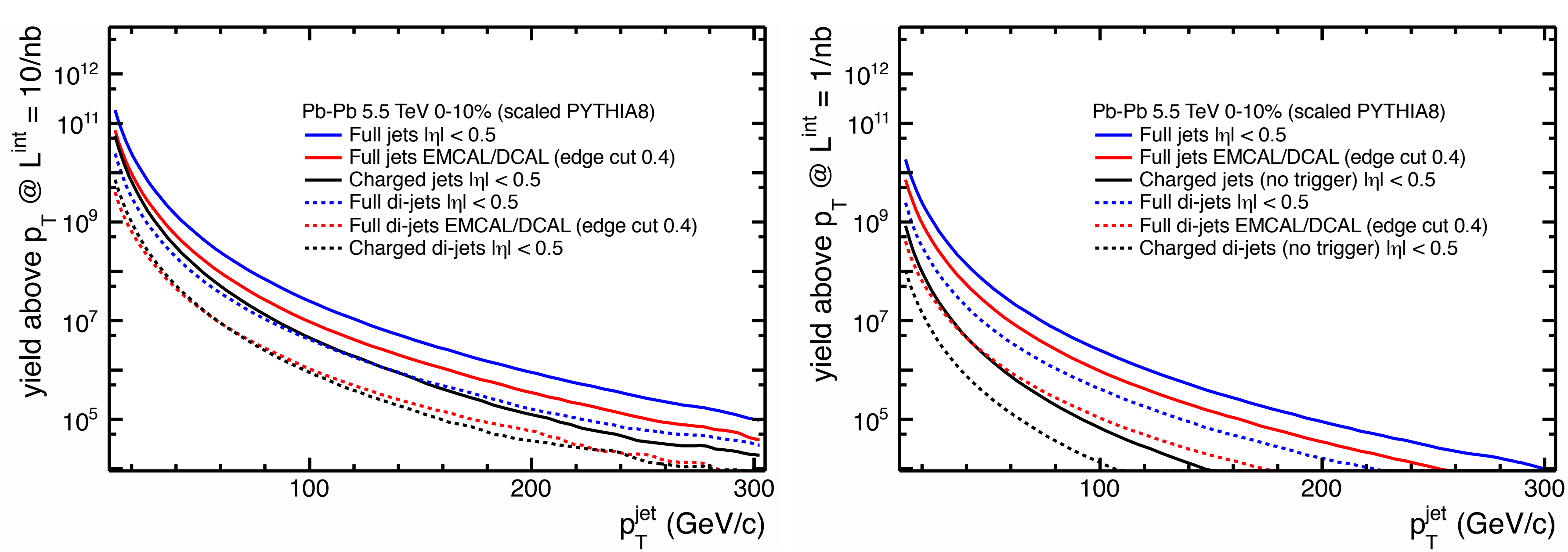


Figure 2.64: Jet yield and number of produced jet-pairs above (leading) p_T -threshold for 0-10% most central Pb–Pb events. The yields are obtained by geometry (T_{AA}) scaled PYTHIA8 simulations, no quenching effects have been considered. Left: After the upgrade. Right: Before the upgrade and with TPC rate limitations in case of the charged jet reconstruction, i.e. no additional triggering on charged jets.

ALICE - Jets and Photons (II)

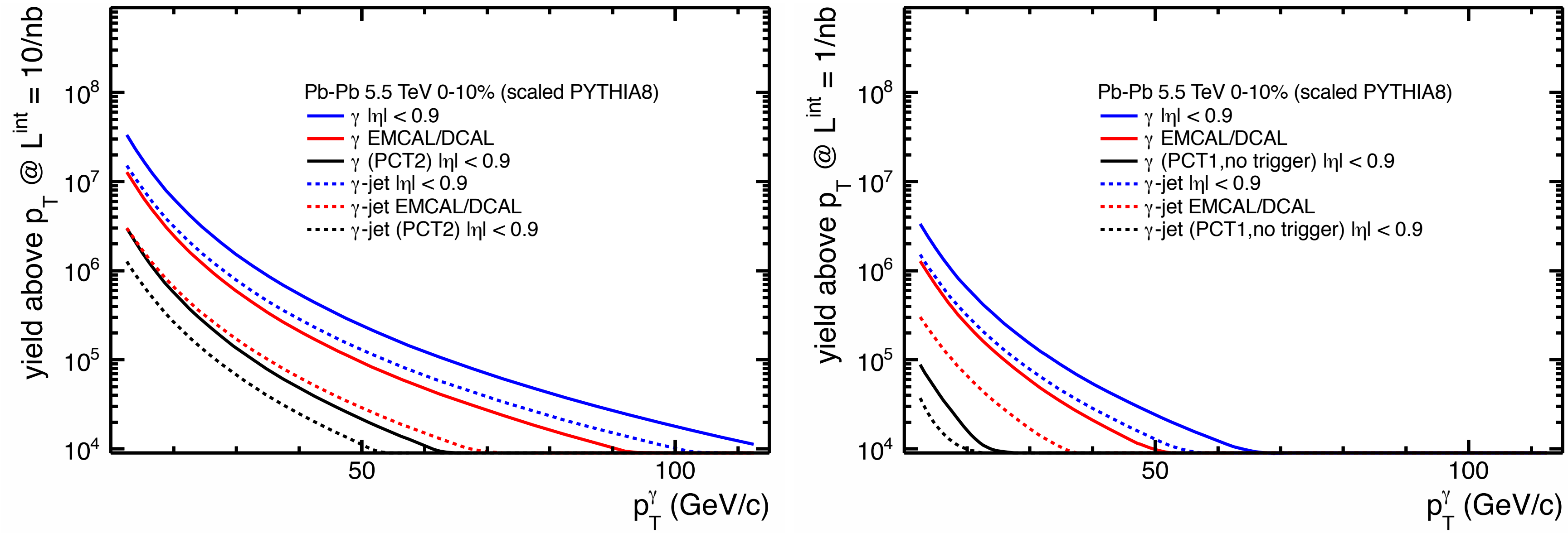


Figure 2.67: Direct photon yield and number of detectable γ–jets above p_{T} -threshold for 0-10% most central Pb–Pb events. The yields are obtained by geometry (T_{AA}) scaled PYTHIA8 simulations. Left: Upgrade scenario. Right: Without upgrade and with TPC rate limitations. In the photon conversion technique reduced reconstruction efficiency due to material thickness has been considered.

ALICE - Jets and Photons (III)

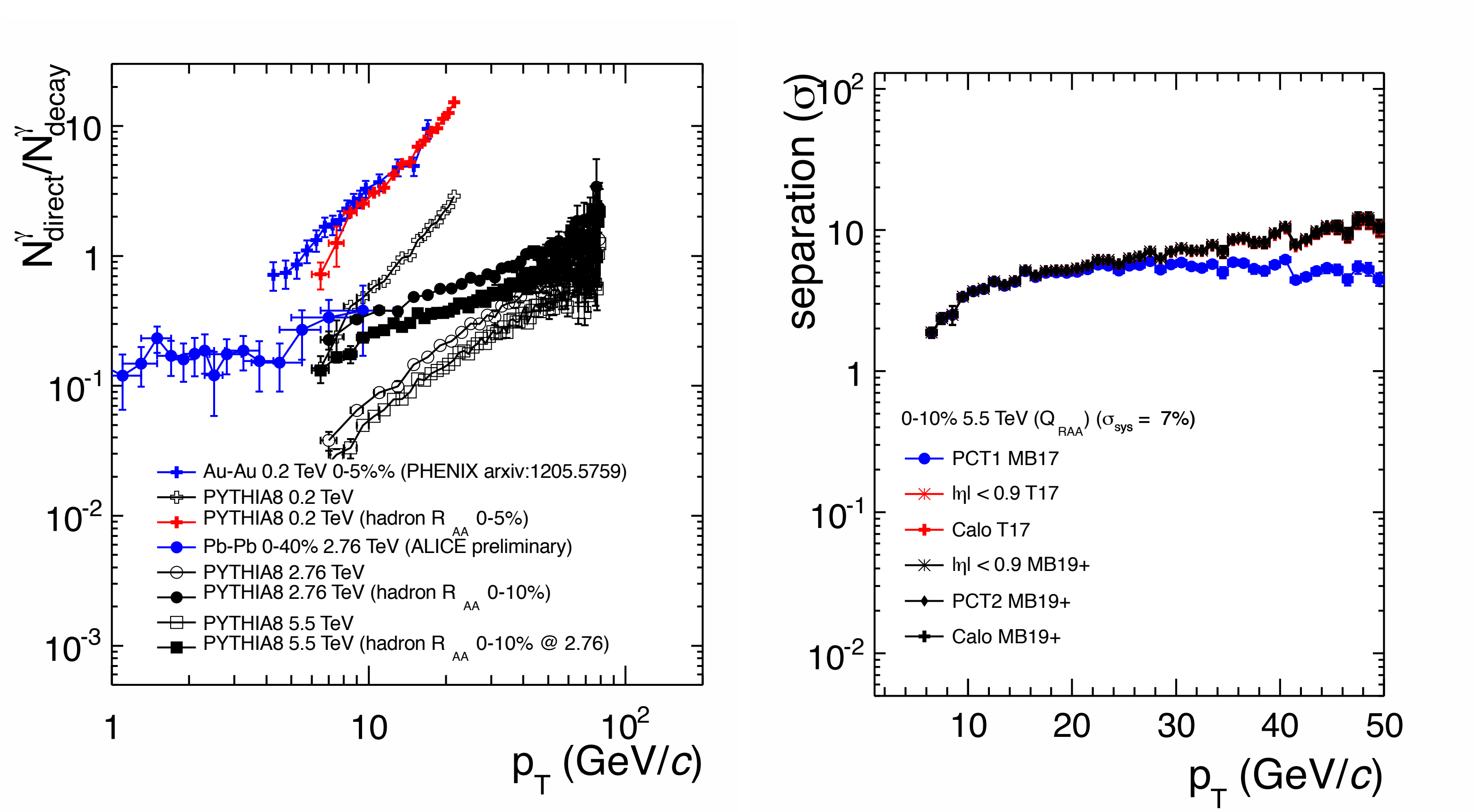
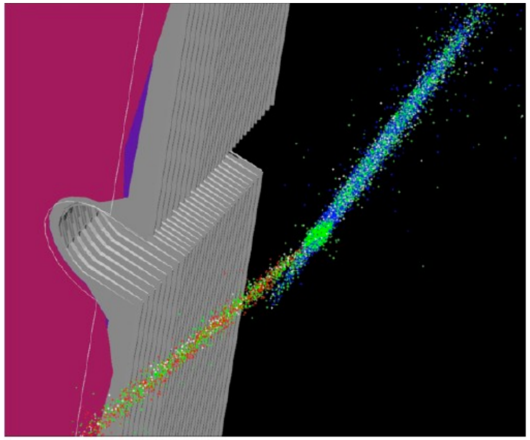


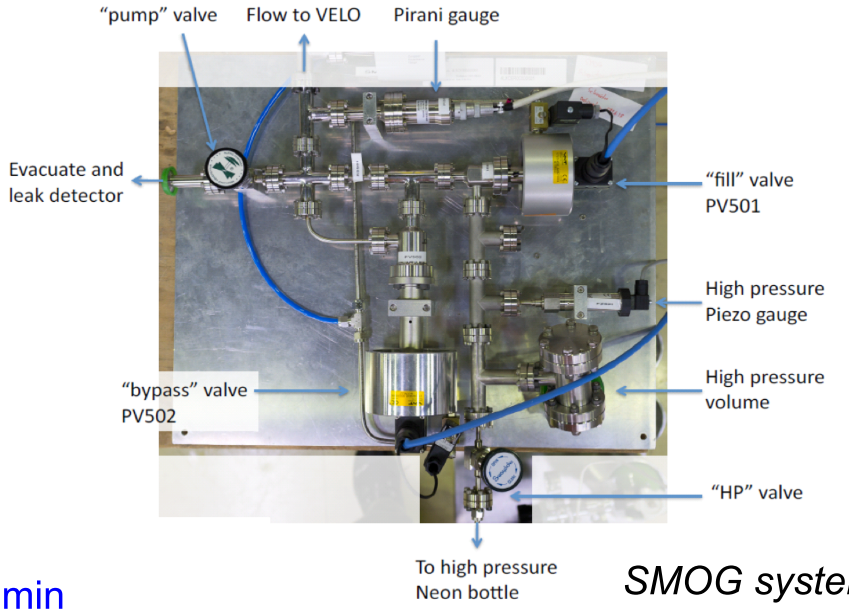
Figure 2.66: Left: Signal-to-background ratio of direct photons to expected decay photons. The suppression of the decay background in heavy-ion collisions has been taken into account by scaling the PYTHIA hadron decay simulation with the measured hadron R_{AA} where available. Right: Projected $n\sigma$ separation of direct photon signal in central Pb–Pb collisions at 5.5 TeV in the double ratio. Systematical (7%) and statistical uncertainties have been combined. The measured hadron R_{AA} in central Pb–Pb collisions at 2.76 TeV has been used to scale the decay background.

LHCb - Fixed Target (SMOG)

→ SMOG: System for Measuring Overlap with Gas:
- Main use so far for precise **luminosity determination**
- Low density noble gas injected in the VELO, in the interaction region
- Only local temporary degradation of LHC vacuum



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.



SMOG system

- pNe pilot run at $\sqrt{s_{NN}}$ = 87 GeV (2012) ~ 30 min
- PbNe pilot run at $\sqrt{s_{NN}}$ = 54 GeV (2013) ~ 30min
- pNe run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 12h
- pHe run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 8h
- pAr run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 3 days
- pAr run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ few hours
- PbAr run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ 1.5 week
- pHe run at $\sqrt{s_{NN}}$ = 110 GeV (2016) ~ 2 days

Preferred target Gas

	He	Ne	Ar	Kr	Xe
A	4	20	40	84	131