Heavy flavours

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DIS2014

XXII. International Workshop on
Deep-Inelastic Scattering and Related Subjects

Disclaimer

- Selection of highlights
- Apologies if your favorite topic is not covered
- My background is heavy-ion physics

Many thanks to the WG5 conveners and speakers!

New results on various topics

- Charm and beauty production
- Heavy quarks as a probe of hot and dense strongly interacting matter
- Rare decays, Mixing and New Physics searches
- Spectroscopy and Quarkonia
- Top-quark physics (jointed session)

Facilities

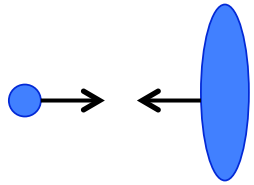
- DESY-HERA
  - H1 and Zeus
- B-factories
  - BABAR and Belle
- BNL-RHIC
  - PHENIX and STAR
- Tevatron
- CERN-LHC
  - ALICE, ATLAS, CMS and LHCb

Charm and beauty production

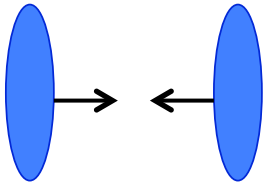
- Elementary ep and pp interactions
  - Test perturbative QCD predictions
  - Study production mechanisms (higher-order contributions)

  Are pp collisions really understood?
  Well modeled in MC generators?

- pA(dA) collisions
  - Study cold nuclear matter effects (shadowing and gluon saturation); initial versus final state effects
  - Sensitive to gluon density at low-x
  - New physics at low-x: Color Glass Condensate?



- Heavy ion collisions
  - Investigate properties of hot and dense QCD matter

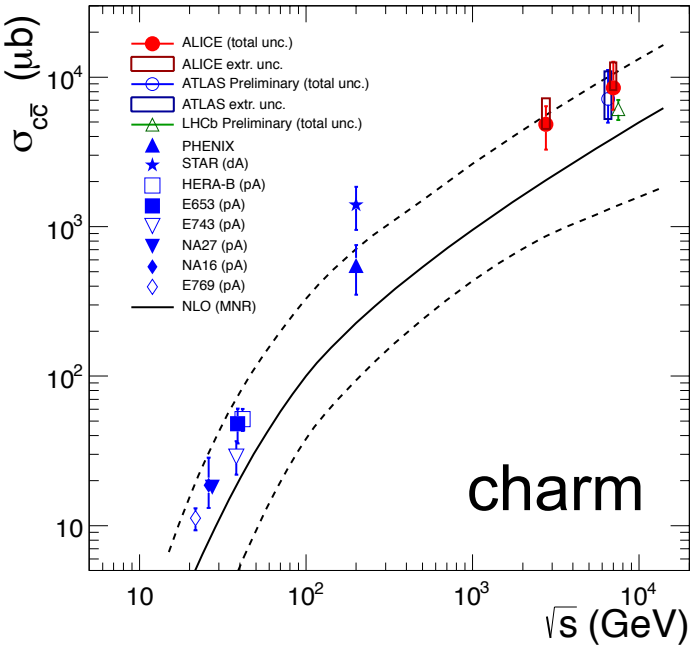


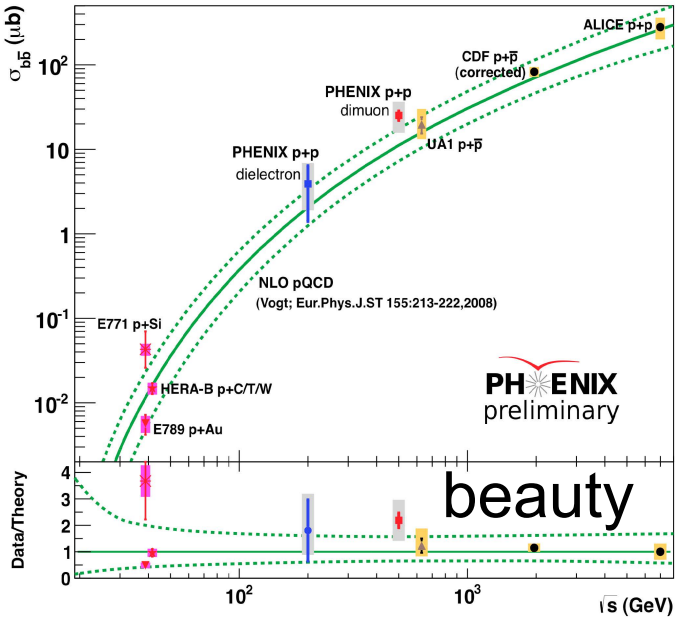
Parallel session: Charm and beauty production

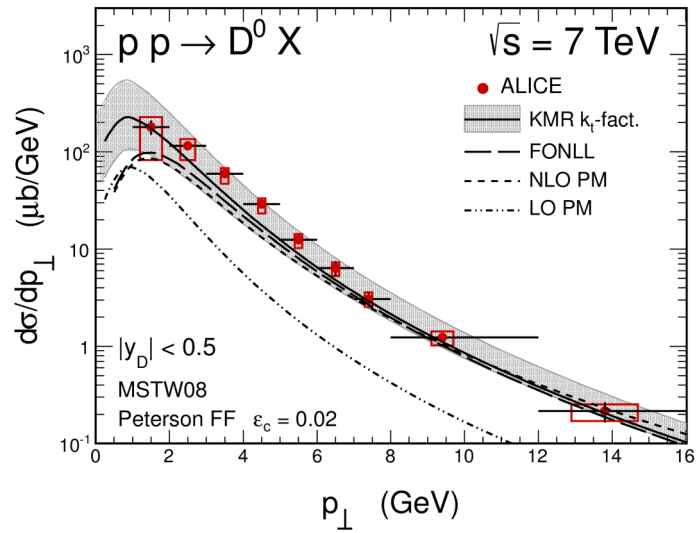
Wednesday morning

- HERA
  - D* photoproduction, Zeus (N. Zakharchuk)
  - D* differential cross-section in deep inelastic ep scattering, H1 and Zeus (M. Lisovyi)
  - Charmonium production, Zeus (N. Kovalchuk)
  - Running of the charm quark mass, Zeus (A. Gizhko)
- LHC
  - Diffractive production of open charm and bottom (M. Luszczak)
  - Heavy-flavour production in pp, p-Pb and Pb-Pb, ALICE (A. Grelli)
  - Quarkonium production in pp, p-Pb and Pb-Pb, ALICE (L.H.A. Manceau)
- RHIC
  - Nuclear matter effects on J/Ψ production, PHENIX (A. Iordanova)

Total production cross sections



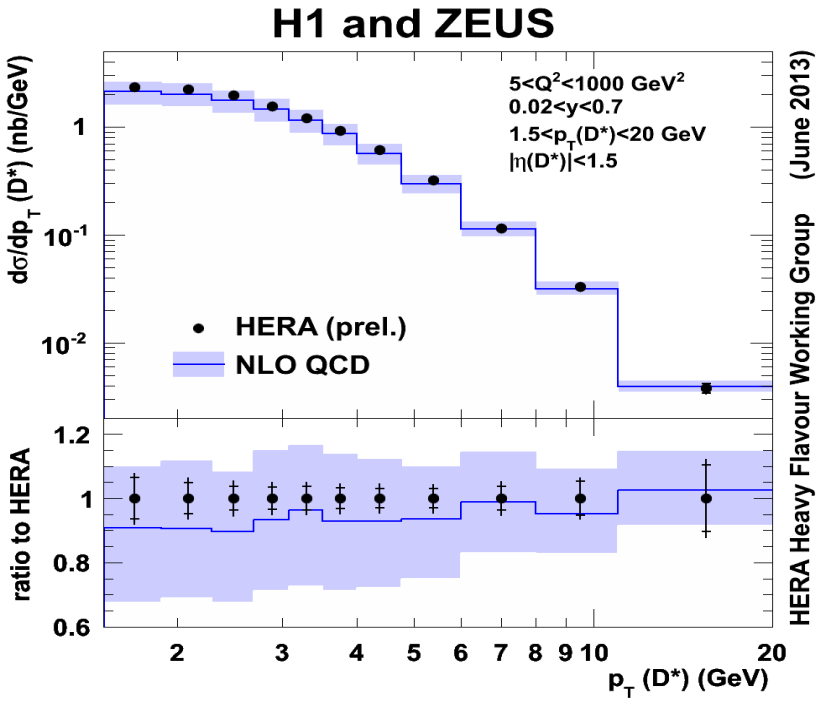


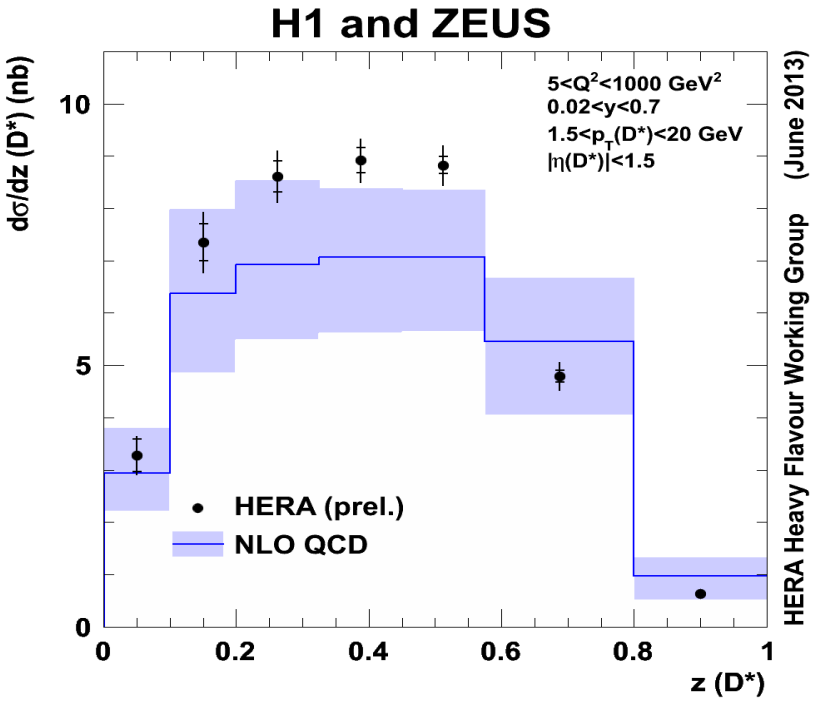


- Data well described by NLO pQCD calculations, although at the upper limit for charm
- Parton spectra from pQCD input for energy loss models

M. Luszczak, Wed morning

Combined D* differential cross section in DIS

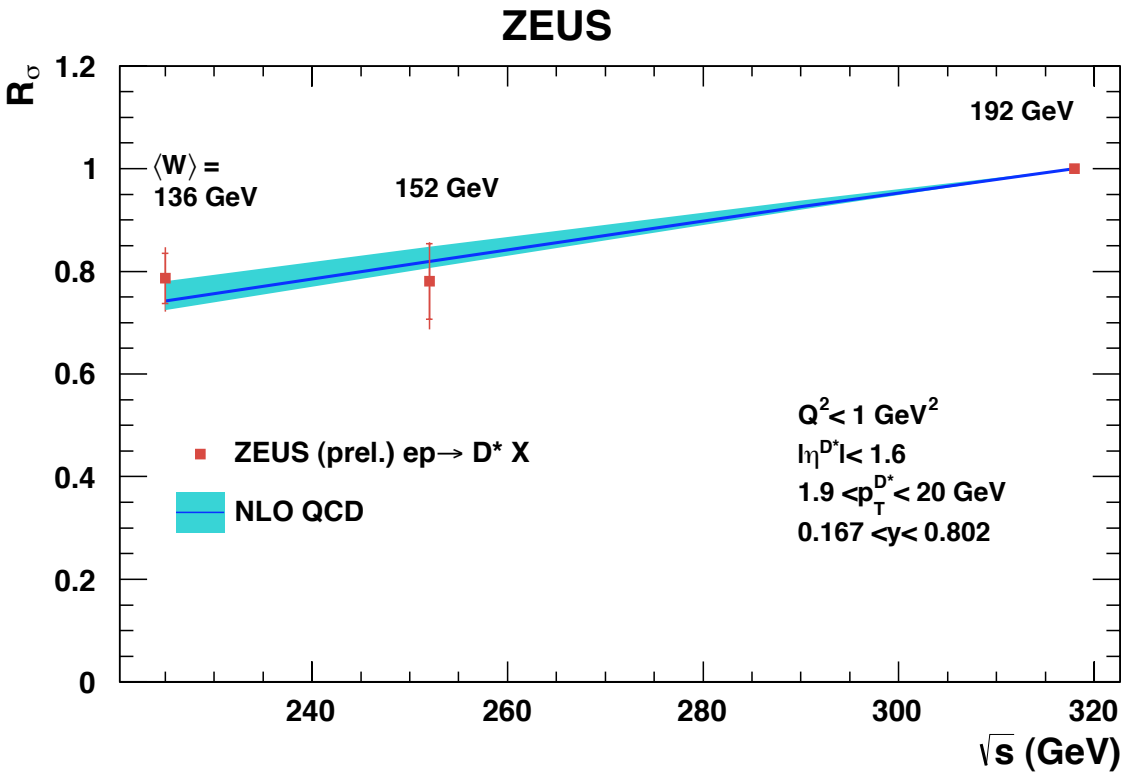




- Significant improvement in precision
- NLO pQCD calculations describe the data reasonably well

M. Lisovyi, Wed morning

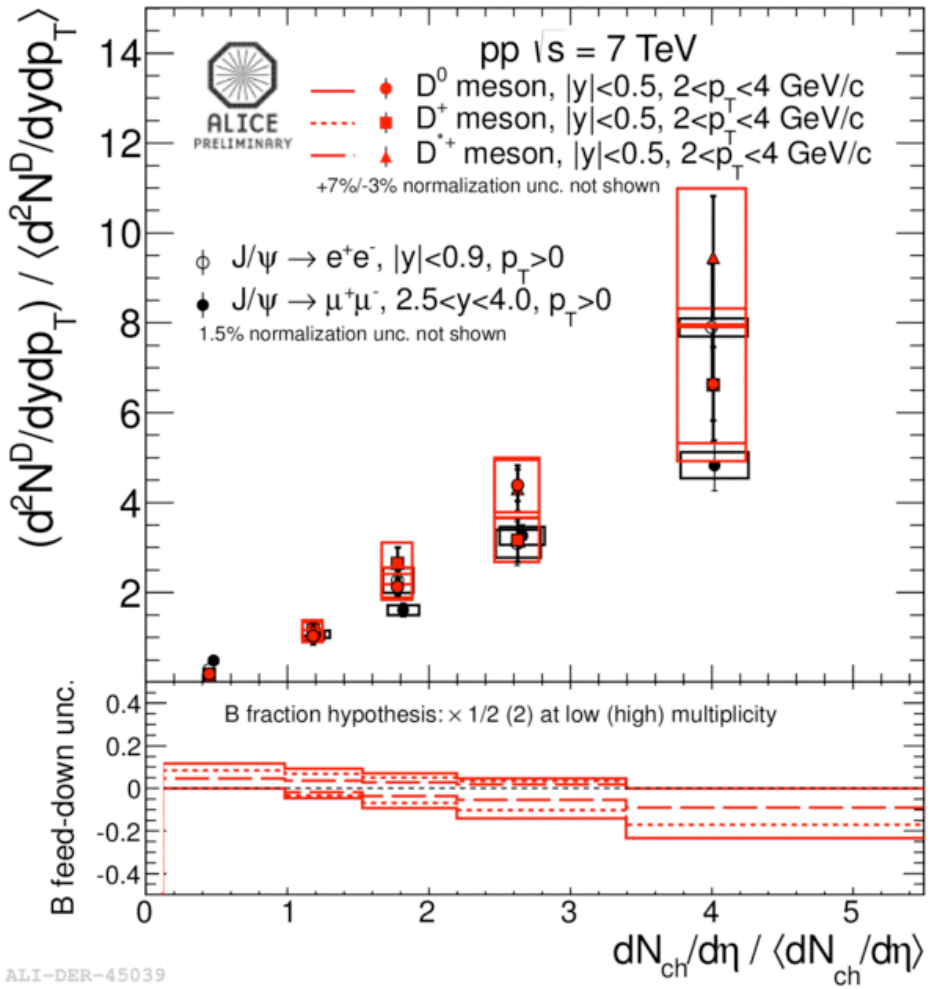
Energy dependence of D* photo-production



N. Zakharchuk, Wed morning

- First measurement at HERA of $\sqrt{s}$ dependence of open charm production
- Observed increase well described by NLO QCD calculations
- Relevant for predictions for future higher energy ep colliders

Multiplicity dependence of D and J/ψ yields in pp



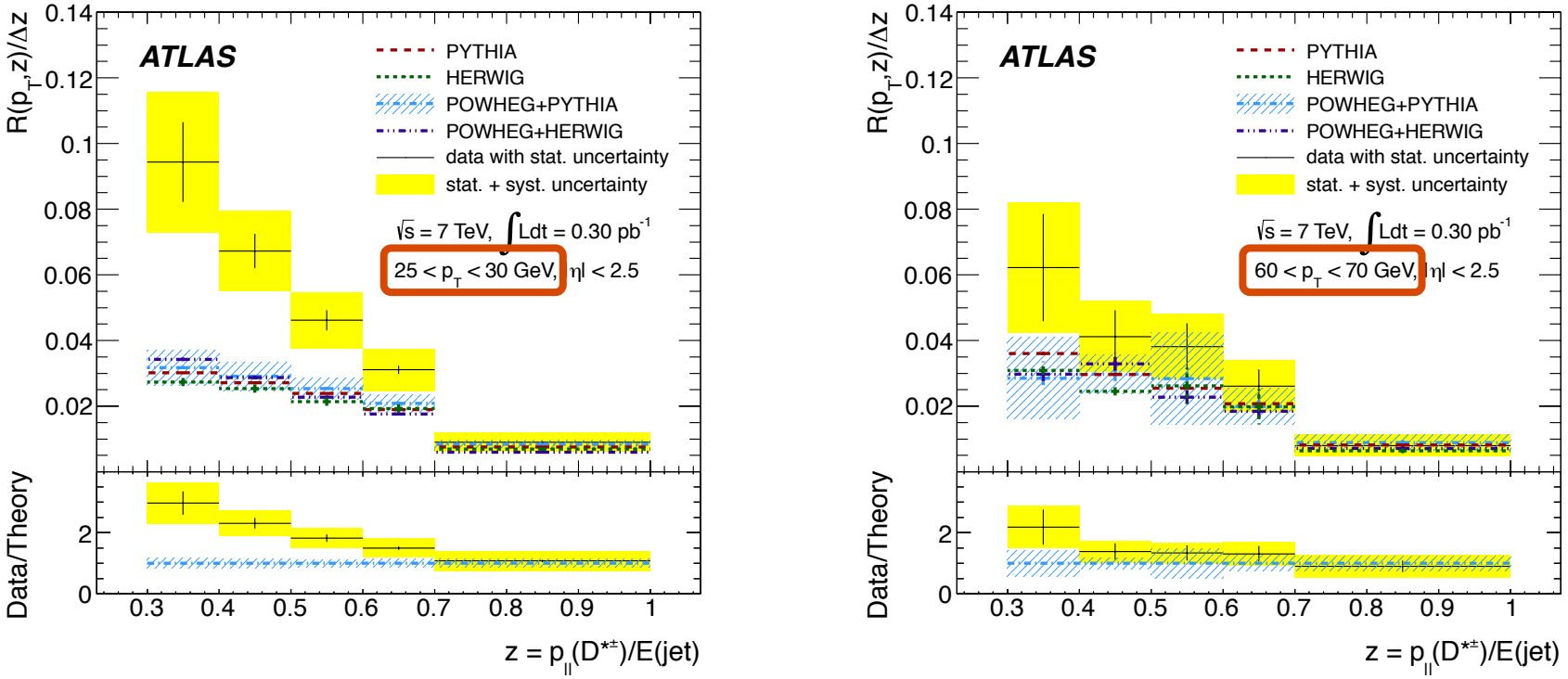
Particle multiplicity

- Linear increase of D-meson yield with charged particle density
- D mesons and J/ψ consistent within uncertainties
- No p_T dependence
- Multi-parton interactions(?) and possible contributions from higher order processes
  - Double parton interaction

A. Grelli, Wed morning

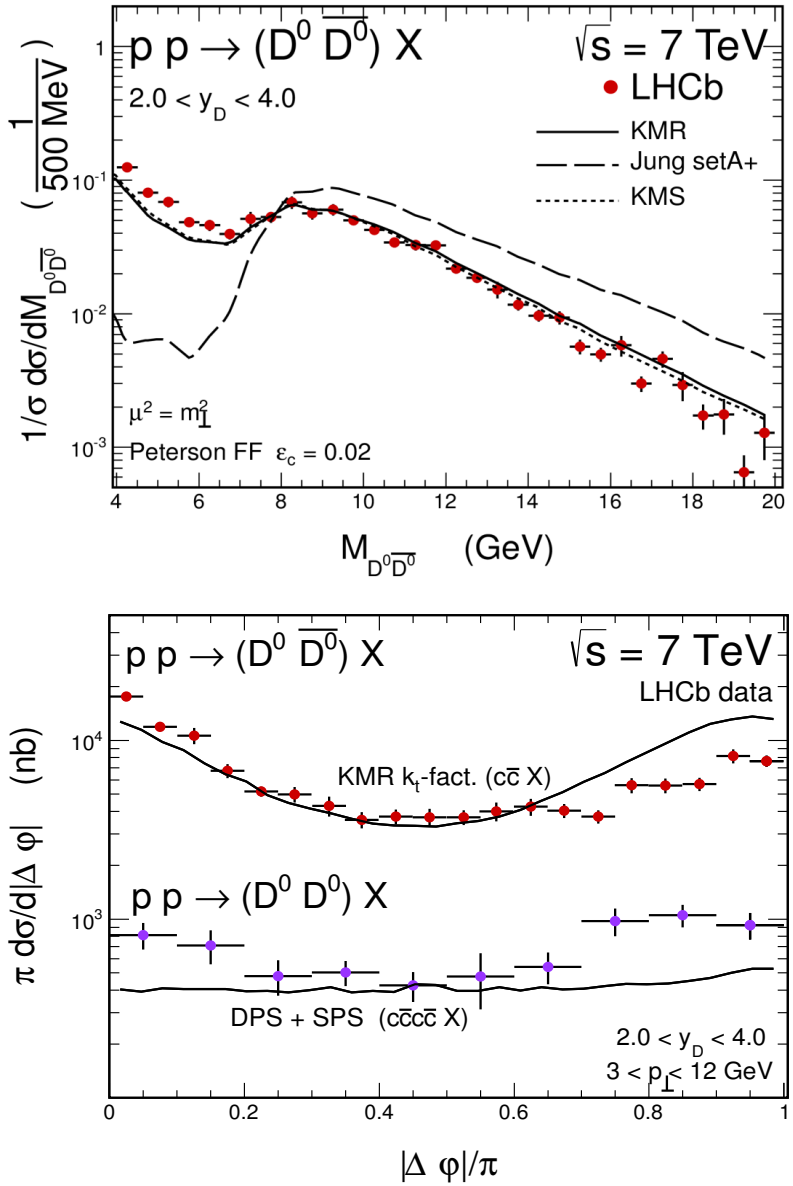
$D^{*\pm}$ production in jets in 7 TeV pp

Phys. Rev. D85, 052005 (2012)



- MC calculations fail to describe data at small z; strongest at low jet transverse momentum
- Indication that jet fragmentation into D^{*+} not well modeled in current MC generators

Charm production in double-parton interactions

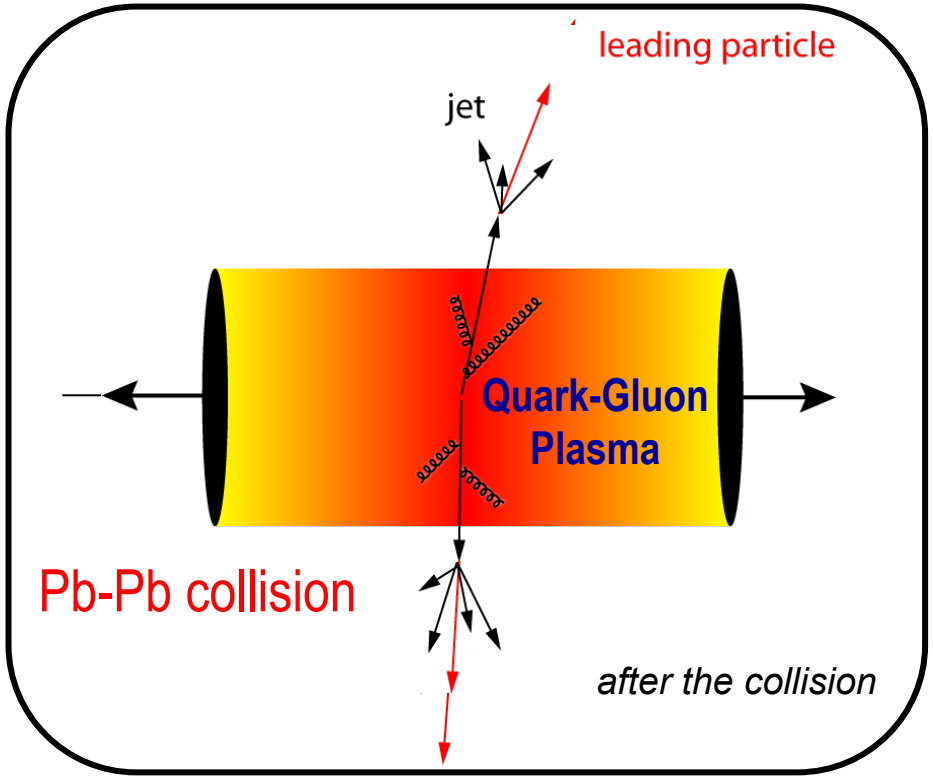


- Single and double parton scattering become comparable at TeV energies (LHC)
- Production of double charm (D-D meson pairs) is an extremely good testing ground of double-parton scattering effects
  - Issue: double-J/ψ production

Phys. Rev. D87, 094022 (2013); arXiv:1402.6972

A. Szczurek, WG4 session, Tue afternoon

Probing hot and dense QCD matter

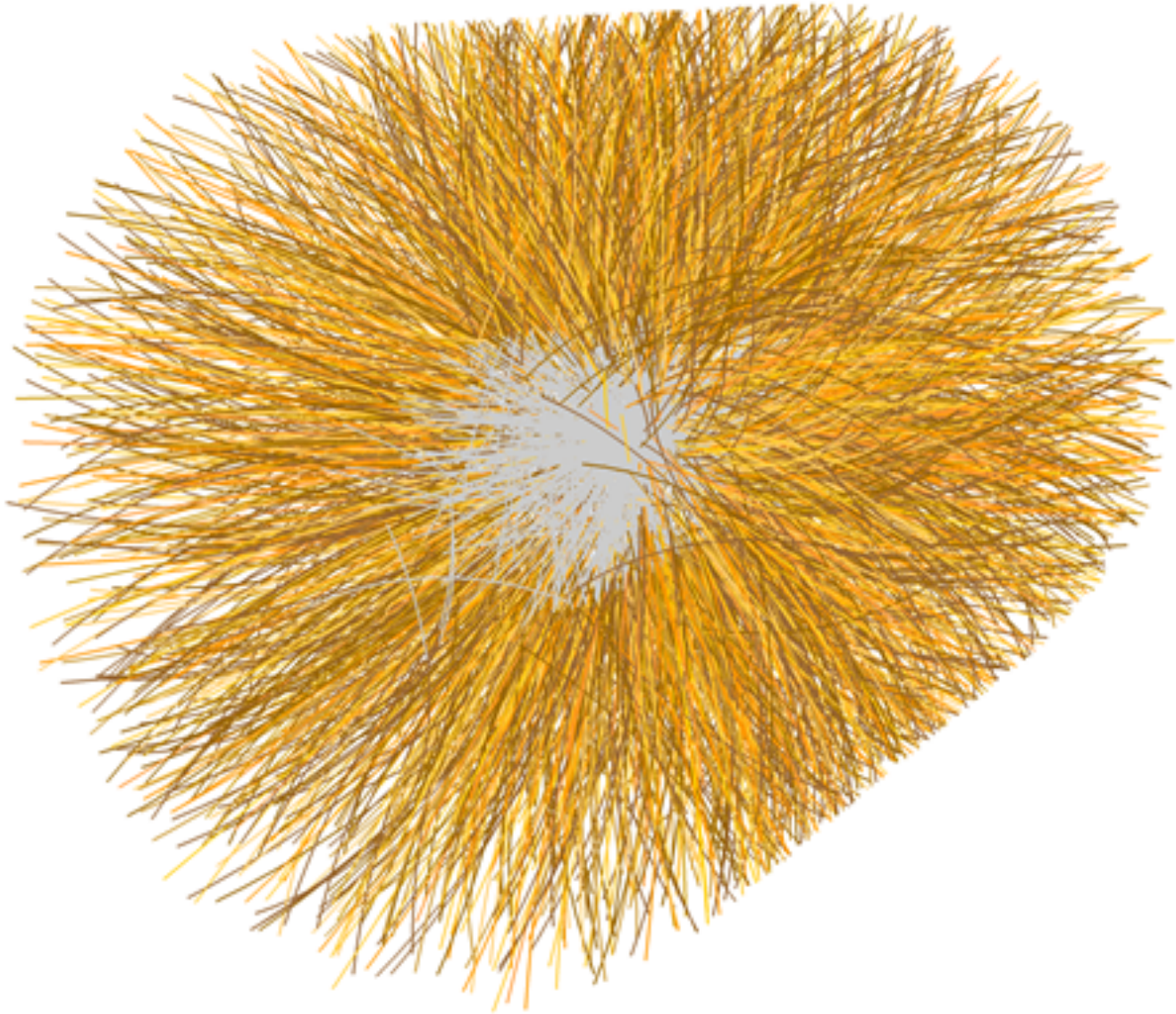


Quantify medium effects with **nuclear modification factor**

$$R_{\mathrm{AA}}(p_T) = \frac{\mathrm{Yield}_{\mathrm{AA}}(p_T)}{\langle N_{bin} \rangle_{\mathrm{AA}} \mathrm{Yield}_{\mathrm{pp}}(p_T)}$$

- "Simplest way" to establish the properties of a system
  - calibrated probe
  - calibrated interaction
  - suppression pattern tells about density profile
- Heavy-ion collision
  - hard processes serve as calibrated probe (pQCD)
  - traversing through the medium and interacting strongly
  - suppression provides density measurement
  - General picture: parton energy loss through medium-induced gluon radiation and collisions with medium

High energy heavy ion collisions



Energy loss of heavy quarks in QCD matter

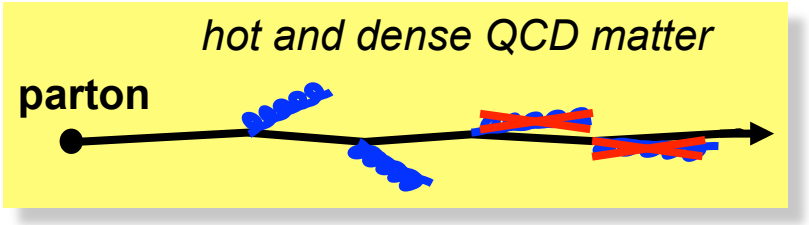
• Radiative parton energy loss is colour charge dependent (Casimir coupling factor C_R)

$$\left\langle \Delta E_{medium} \right\rangle \propto \alpha_S C_R \hat{q} L^2$$

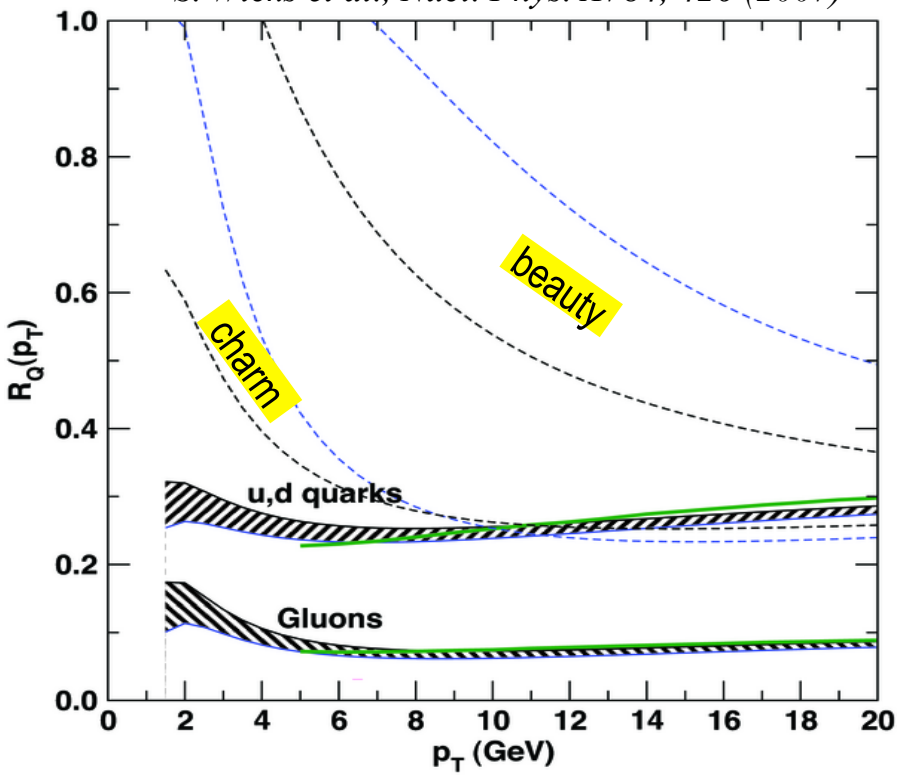
• Dead-cone effect: gluon radiation suppressed at small angles ($\theta < m_Q/E_Q$)

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

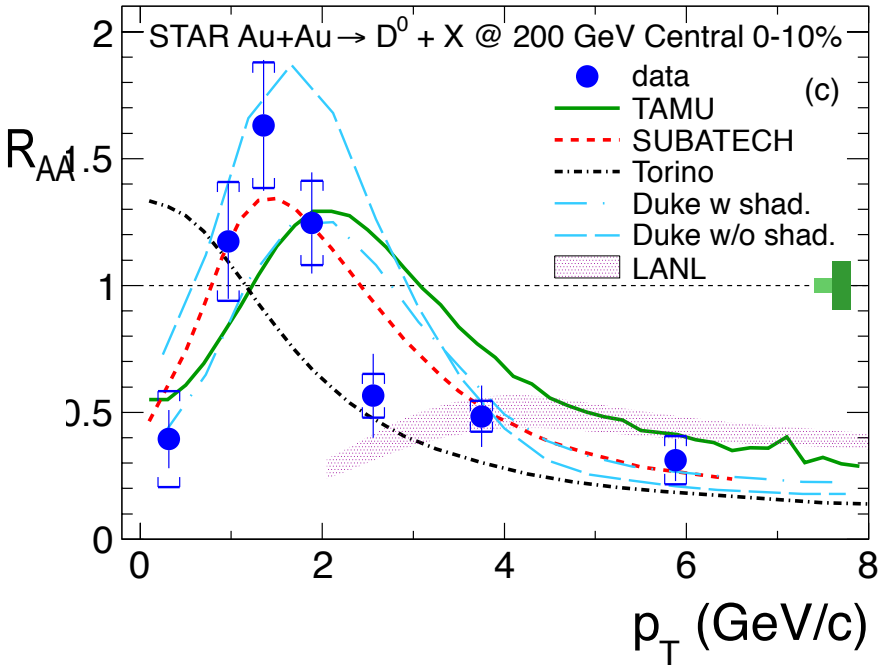
$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

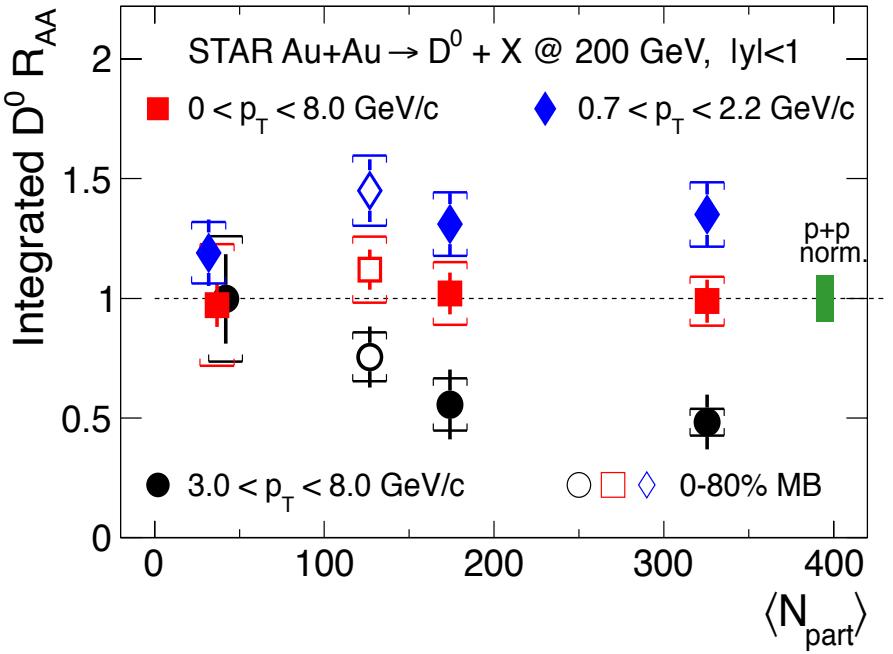


S. Wicks et al., Nucl. Phys. A784, 426 (2007)



R_{AA} of D^0 mesons at top RHIC energies

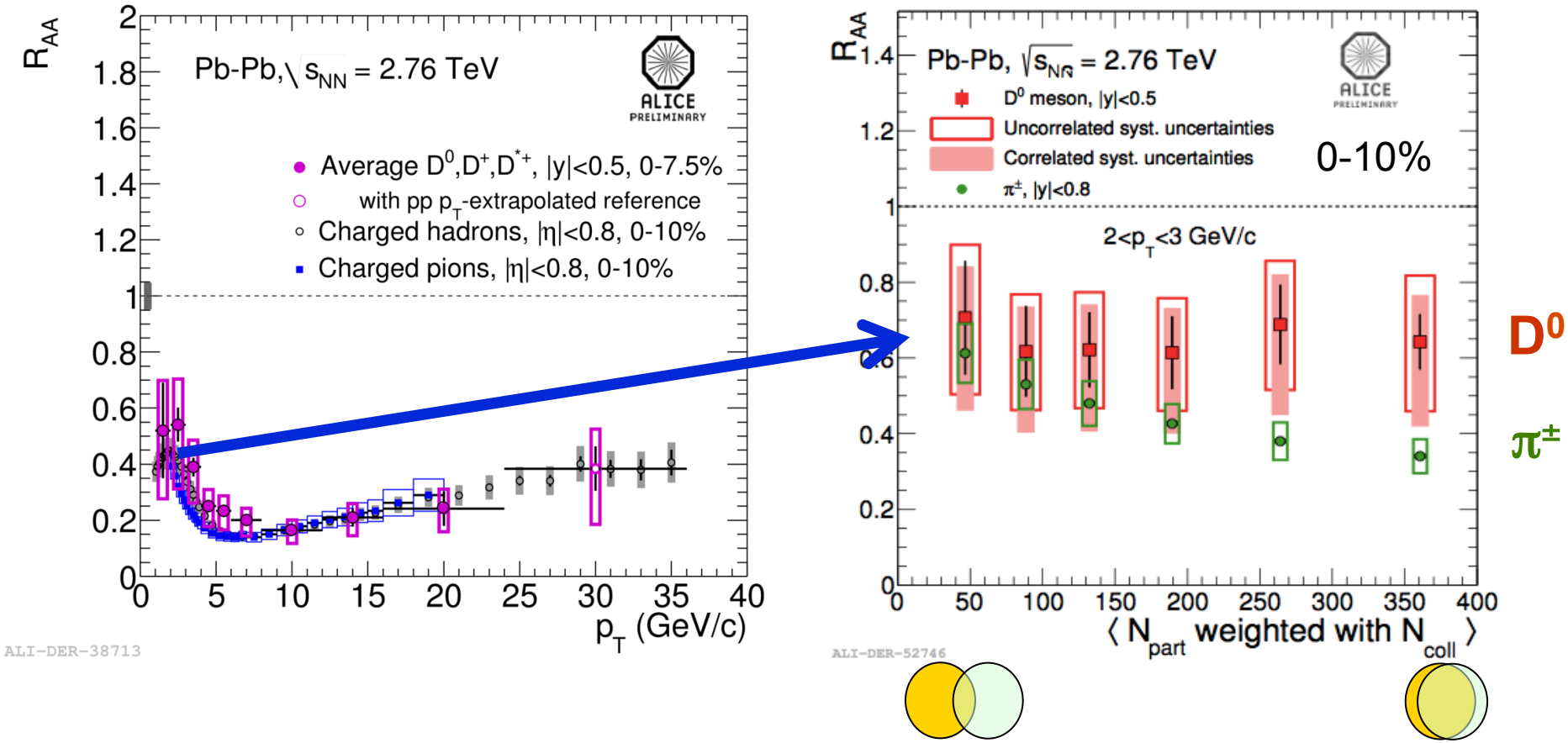




- Suppression by a factor of about 2 at high p_T for most central Au-Au collisions
- Enhancement at intermediate p_T: Coalescence of charm with a light quark from the medium

arXiv:1404.6185

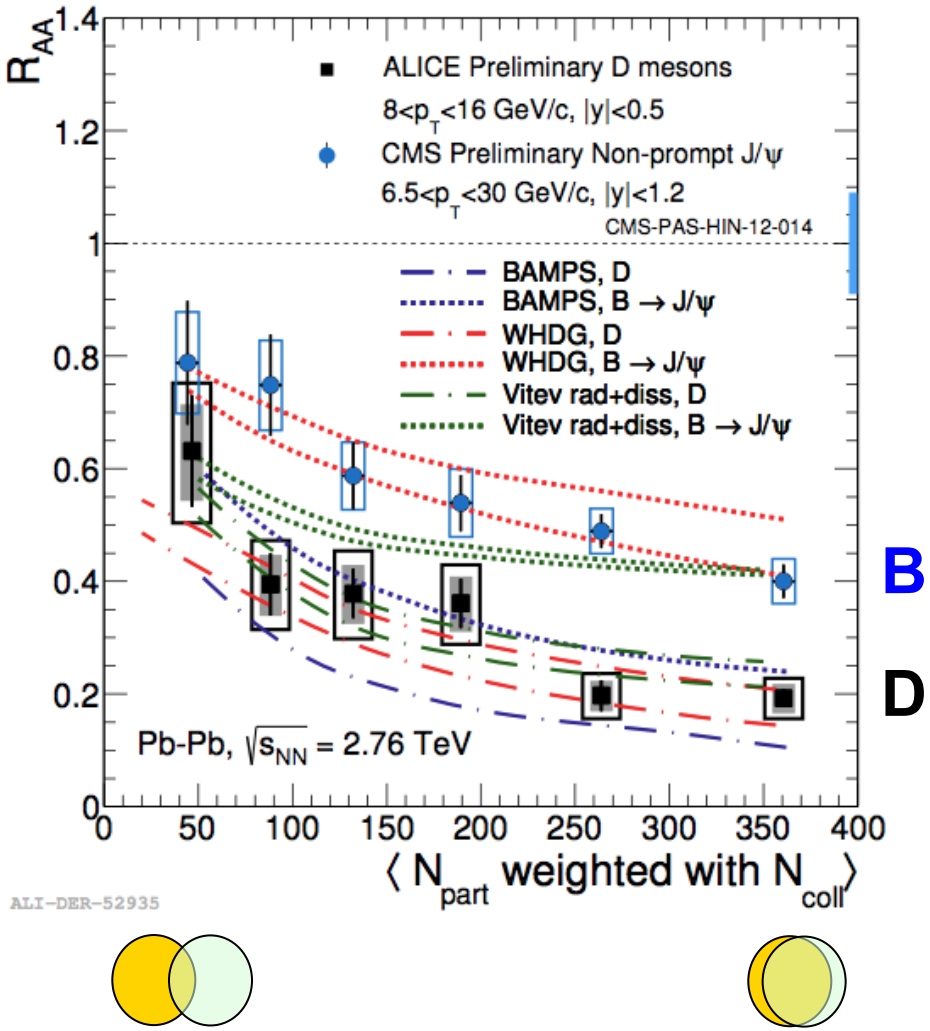
R_{AA}: light versus heavy quark hadrons at LHC



Strong suppression (factor 4-5) above 5 GeV/c in most central Pb-Pb, compared to binary scaling from pp

$R_{AA}^{\text{D meson}} > R_{AA}^{\text{pions}}$ at low p_T? → More data needed for final conclusion

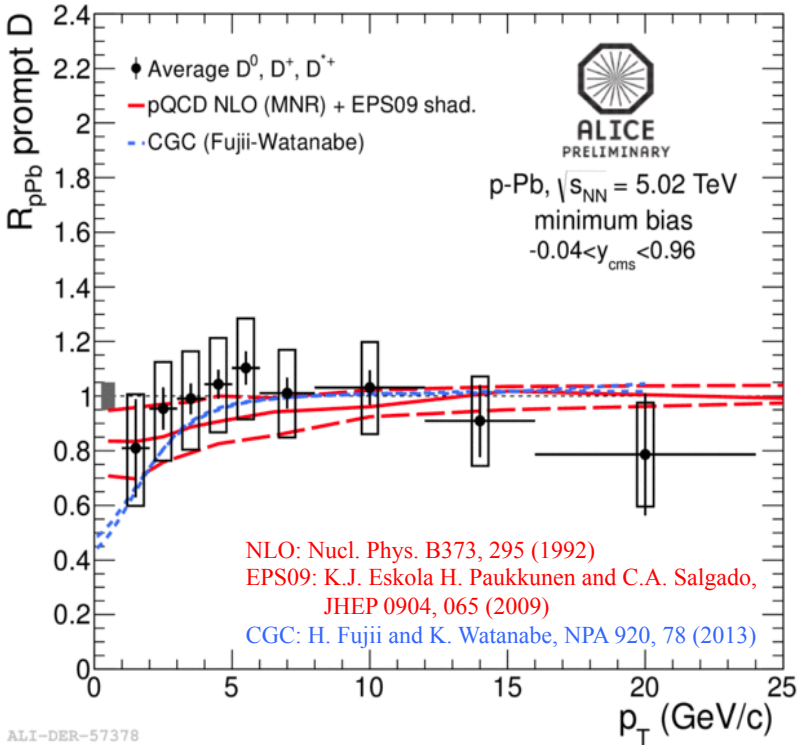
R_{AA} of D and B mesons

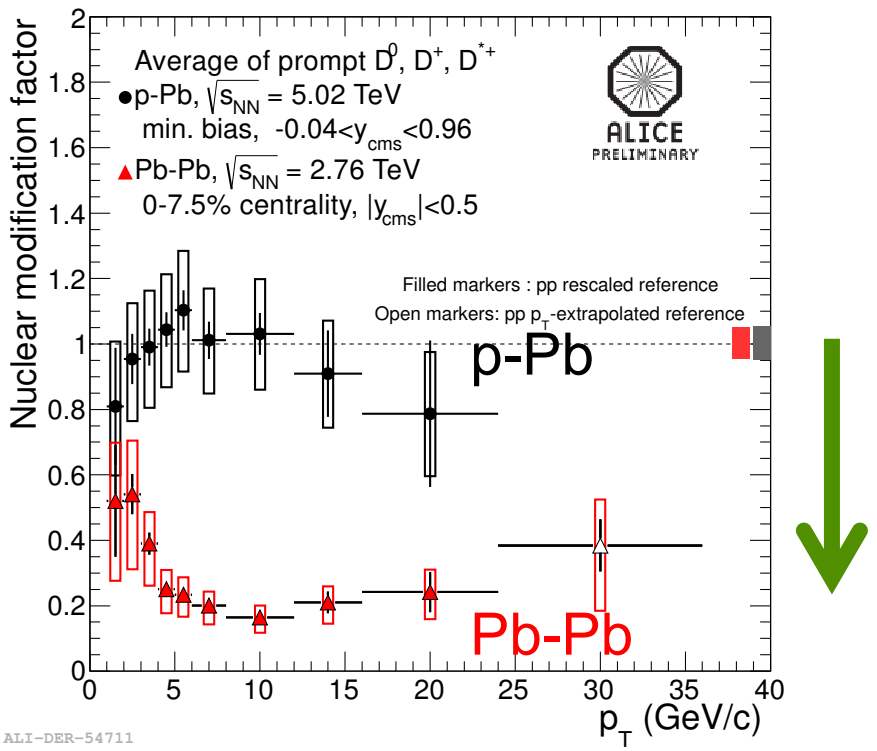


- Comparison of prompt D mesons (ALICE) with J/ψ from beauty decays (CMS)
- D and B meson $\langle p_T \rangle$ ~10 GeV/c
- First indication of 'heavy-quark mass' dependence of the energy loss: $R_{AA}^{D} < R_{AA}^{B}$

A. Grelli, Wed morning

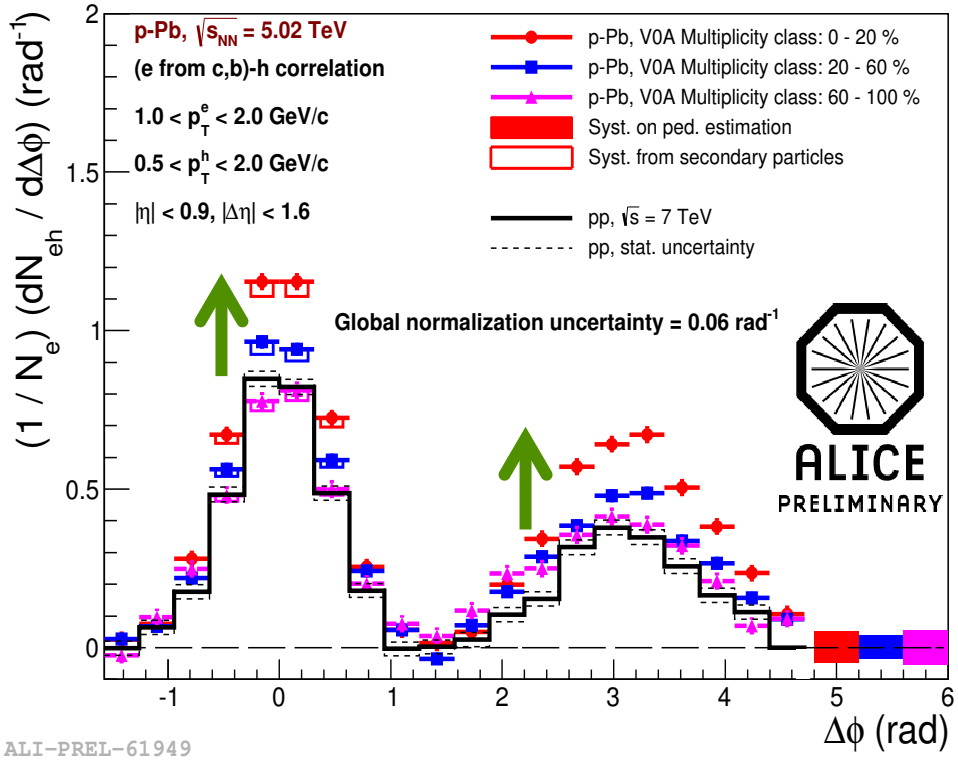
p-Pb data: Probe initial state effects





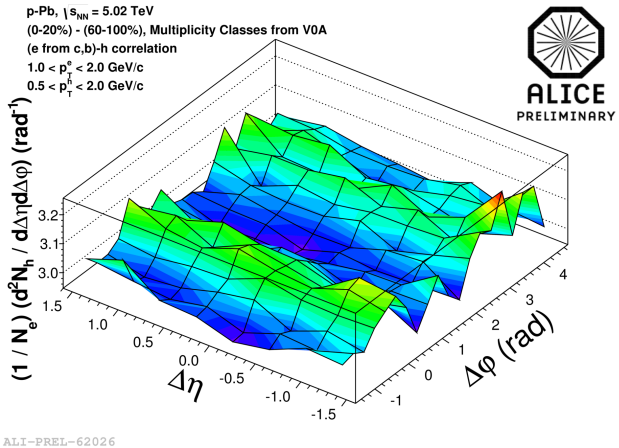
- Important baseline measurement of **cold nuclear matter (CNM) effects** (Cronin effect, nuclear shadowing and gluon saturation)
- D meson R_{pA} shows consistency with unity and predictions from shadowing and *Colour Glass Condensate* models
- **High-p_T suppression of particle yield in Pb-Pb is a final state effect**

Azimuthal correlations in p-Pb: a surprise



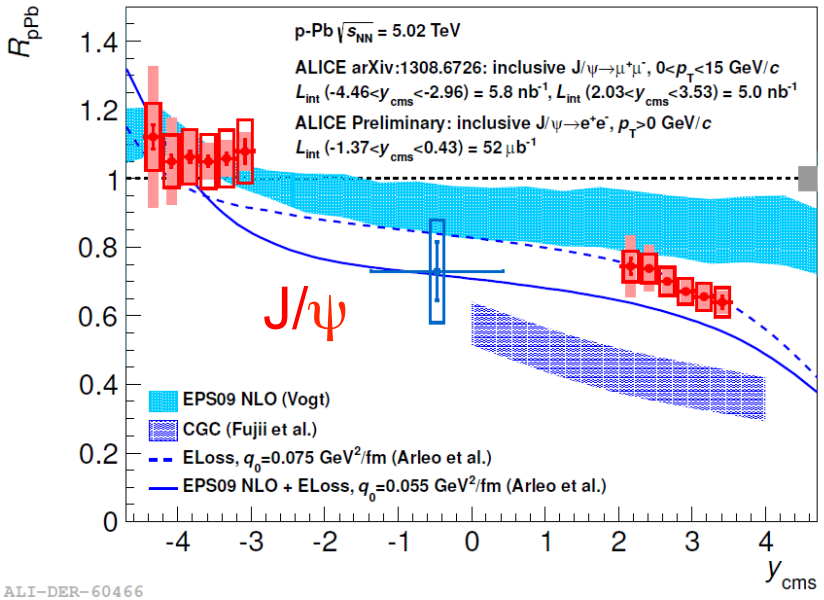
Azimuthal angular correlation between heavy-flavour decay electrons and charged hadrons

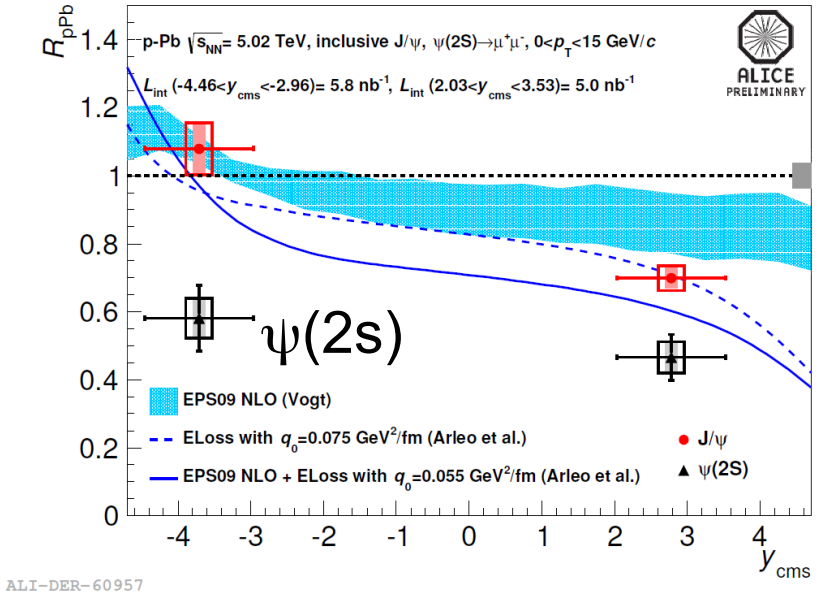
- Three multiplicity classes
- Most central events have higher correlation yield for low-p_T electrons
- Indication for **long-range correlation** in $\Delta\eta$
- Advanced model calculations needed



Difference of the correlation distribution for high and low multiplicity

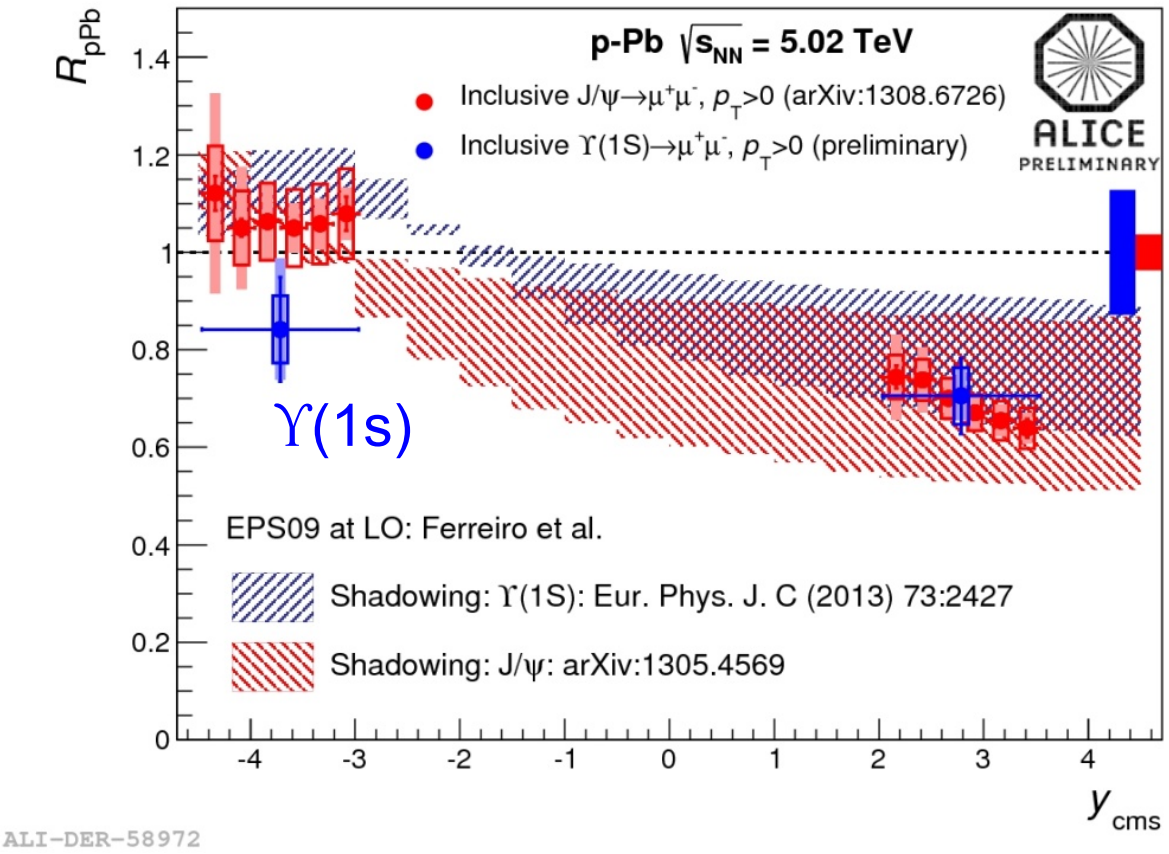
Quarkonia production in p-Pb collisions





- Significant suppression at mid- and forward rapidity
- Gluon saturation model underestimate J/ψ data
- Shadowing model CEM + EPS09 NLO give reasonably good description for J/ψ but not for ψ(2S)
- J/ψ and ψ(2S) are not affected in the same way by CNM effects
  - Sizeable final state effects for ψ(2S) (lower binding energy)

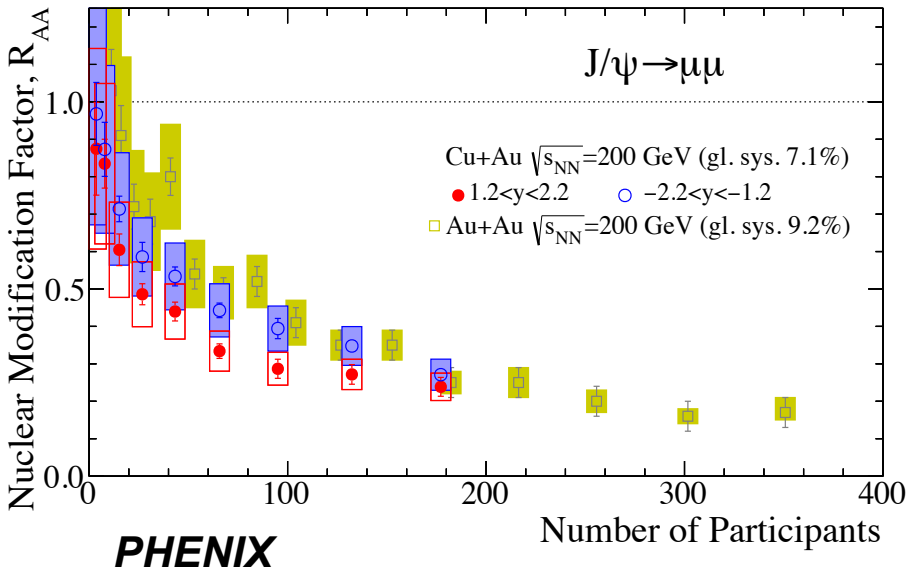
Quarkonia production in p-Pb collisions (cont'd)

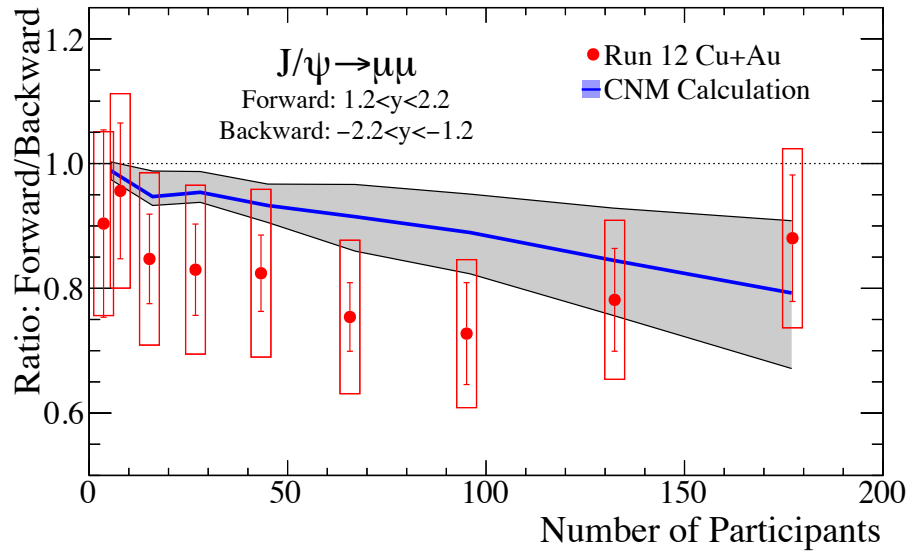


L. Manceau, Wed morning

- Similar R_{pPb} of J/ψ and ϒ(1s)
- EPS09 shadowing in fair agreement within uncertainties

CNM effects in Cu+Au collisions at RHIC



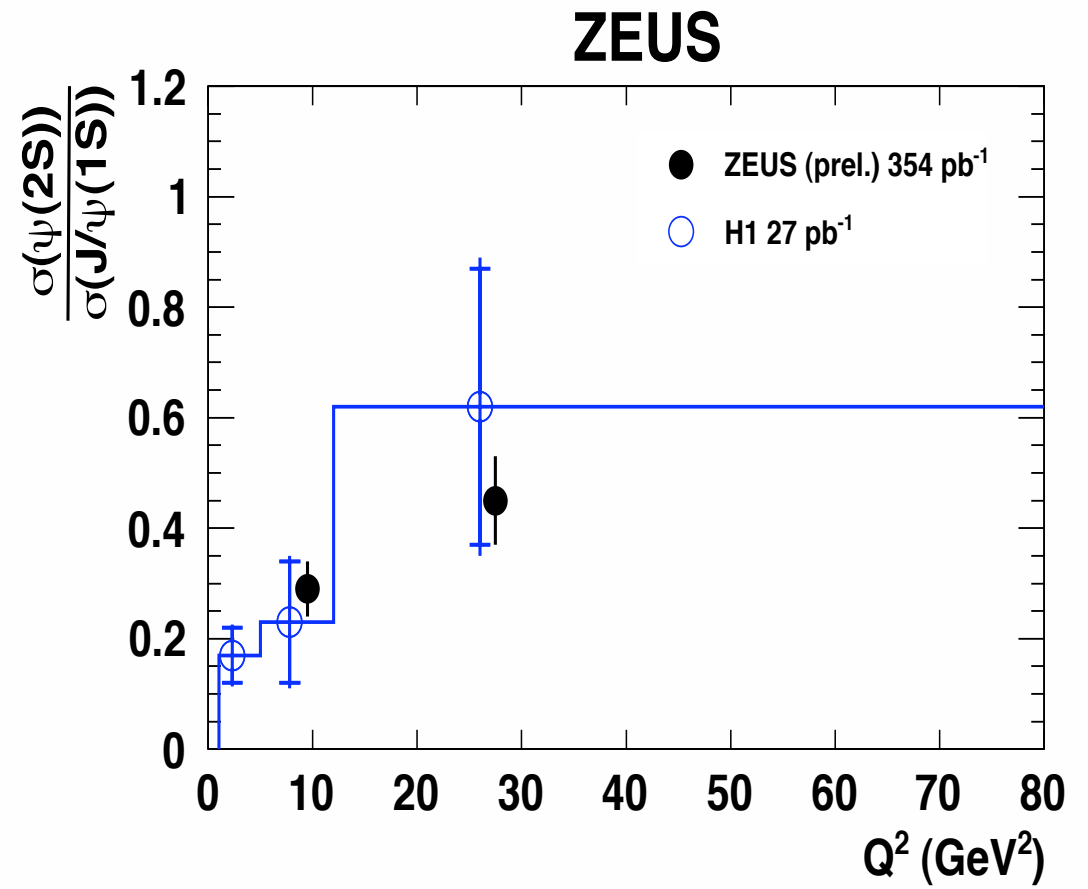


- Cu+Au: Cu-going direction
  - stronger suppression than in Au+Au at same N_{part}
- Forward/backward ratio
  - shadowing effect comparable with data
- Also J/ψ in U+U

A. Iordanova, Wed morning

arXiv:1404.1873

Charmonium production at HERA



Di-muon channel

- Exclusive production of ψ(2S) and J/ψ(1S) in DIS
- Cross-section ratios reasonably independent of Q^2, W and t
- Theoretical model calculation missing

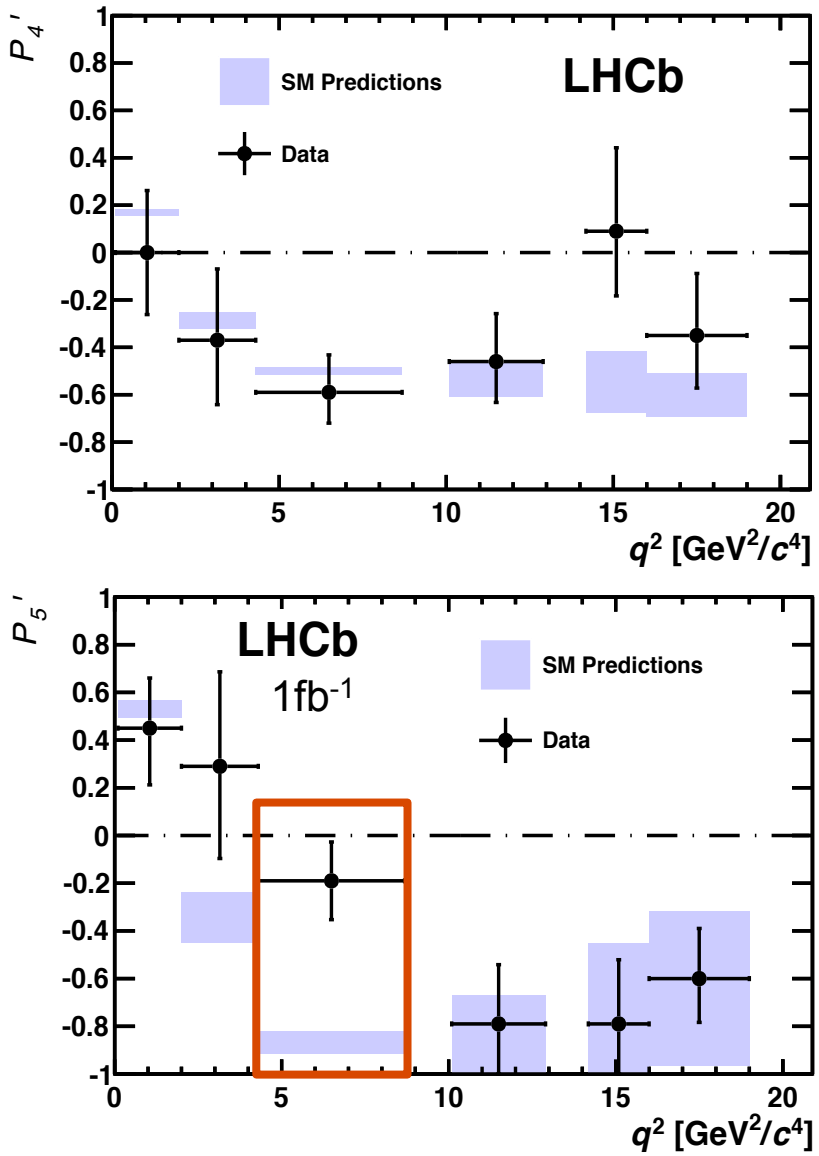
N. Kovalchuk, Wed morning

Parallel session: B meson decays

Wednesday afternoon

- Theory
  - Overview on $B_{s,d} \rightarrow \mu^+\mu^-$ decays (R. Knegjens)
  - Perturbative contributions to rare B decays (M.K. Misiak)
  - Comprehensive Bayesian analysis of rare (semi-)leptonic and radiative B decays (D. van Dijk)
  - Space for New Physics in neutral B mixing observables (G. Tetlalmatzi-Xolocotzi)
- B-factories
  - EW and radiative penguin processes in B decays, Belle (Y. Kwon)
  - Radiative B decays and new physics searches, BABAR (L. Sun)
- LHC
  - Rare decays, LHCb (O. Leroy)
  - Rare and suppressed processes in B decays, ATLAS (V. Nikolaenko)
  - Lifetime of flavoured hadrons, LHCb (P. Sail)
  - Study of the Λ_b decay properties, ATLAS (T. Agatonovic-Jovin)

$B^0 \rightarrow K^{*0}\mu^+\mu^-$



- Rare B decays are sensitive to New Physics
- b→s transitions only occur through loop/box processes - flavor violation beyond the SM
- 3.7σ discrepancy in P5′
- Might be due to large power corrections or New Physics
- More data available (1 fb^{-1} → 3 fb^{-1})

Phys. Rev. Lett. 111, 191801 (2013)

Parallel session: Spectroscopy and Quarkonia

Thursday morning

- B-factories
  - Studies of quarkonium production, BABAR (G. Cibinetto)
  - Spin effects in Bottomonium, Belle (U. Tamponi)
  - Search for doubly-charmed baryons and study of charmed-strange baryon states, Belle (Y. Kato)
- LHC
  - Production of charmonium(-like) and their botomonium counterparts, ATLAS (S. Cheatham)
  - Quarkonia and quarkonia-like spectroscopy, LHCb (T. Skwarnicki)
  - Charmed spectroscopy, LHCb (L. Zhong)
  - Spectroscopy and decay properties of b-hadrons, ATLAS (A.S. Chisholm)
  - Properties and decays of B_c mesons, LHCb (L. Anderlini)
- Theory: Heavy quarkonium spectroscopy with effective field theories for non-relativistic particles (A. Vairo)

Quarkonia-like states

- Exotic hadrons: four-quark states
- Charmonium(-like) states:
  - X(3872): observed in more than one decay channel
  - Y(4260)
  - $Z(4430)^+$: Recently confirmed by LHCb; Belle found yet another charged Z in $B \rightarrow J/\Psi K\pi$ channel
- Bottomonium(-like) states
- B-factories re-defined our understanding of hadrons; classification not possible within traditional quark model
- Product branching fractions of XYZ states are small ~10^{-6} → High luminosity exp.: BESIII, LHCb, Belle II

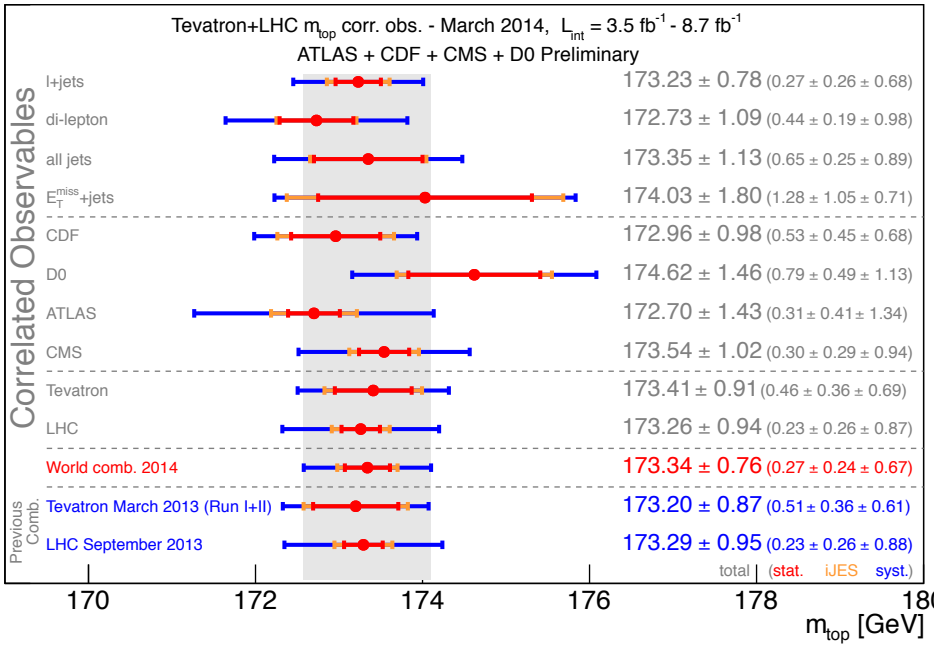
Parallel session: Top-quark physics

Jointed session with WG3, Tuesday afternoon

- Top quark cross section
  - CMS (J. Fernandez Menendez)
  - ATLAS (P. Skubic)
- Single top quark production
  - CMS (A.O.M. Iorio)
  - ATLAS (C. Monini)
- Top quark properties
  - ATLAS (R. Di Sipio)
  - CMS (E. Bouvier)
- Top quark pair properties
  - ATLAS (R. Schafer)
- Higgs and ttbar predictions from CTEQ-TEA (C. Schmidt)
- Associated production of heavy flavour and search for H→bb (R. Castello)
- Top quarks as a probe for heavy new physics (C. Degrande)

Top-quark production

- Improved precision of measurements
- Now focus on better understanding of production mechanism
  - Detailed comparisons with state-of-the-art QCD predictions
  - Possibly find deviations from the SM



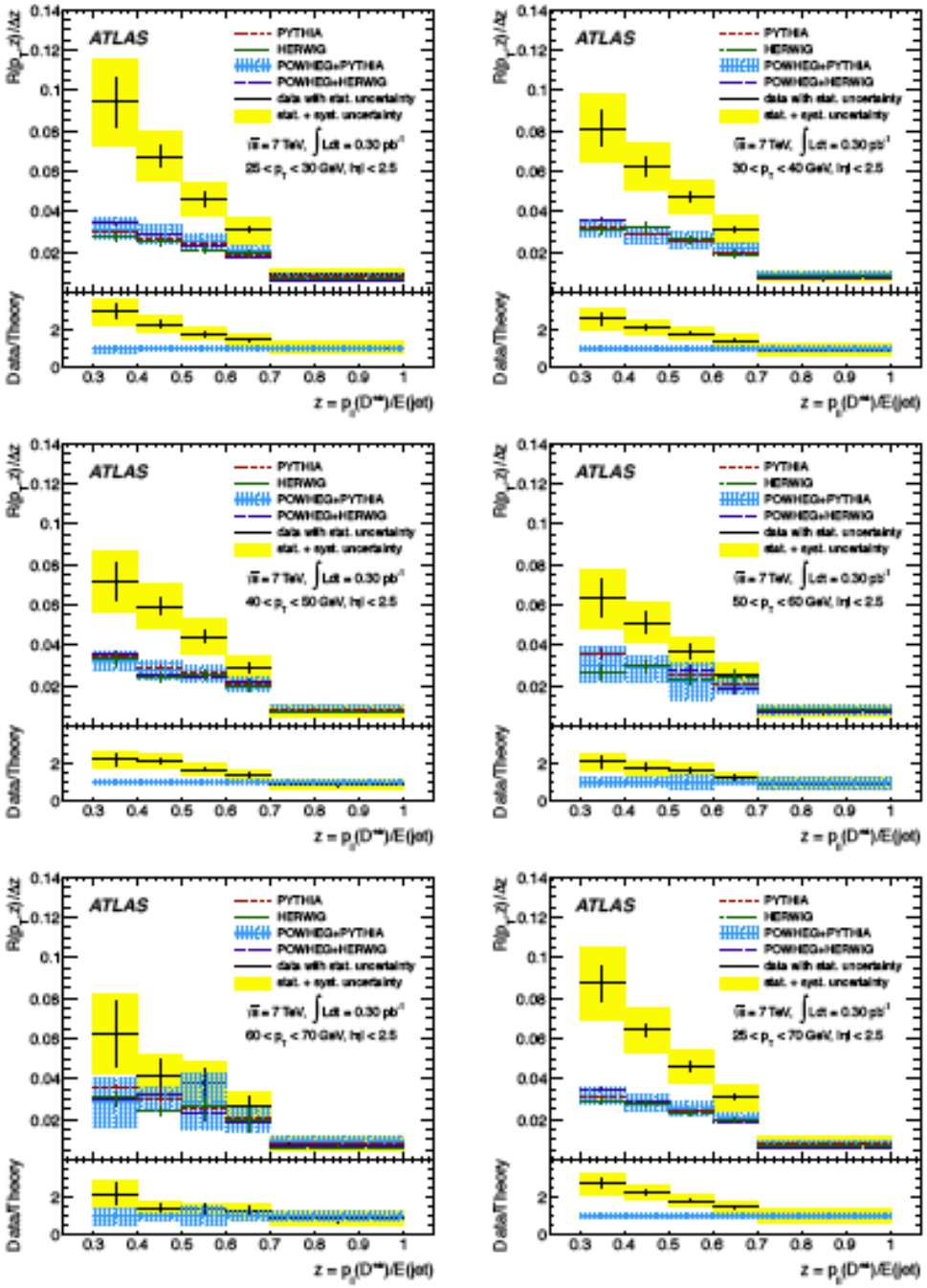
Top mass: LHC/Tevatron combination

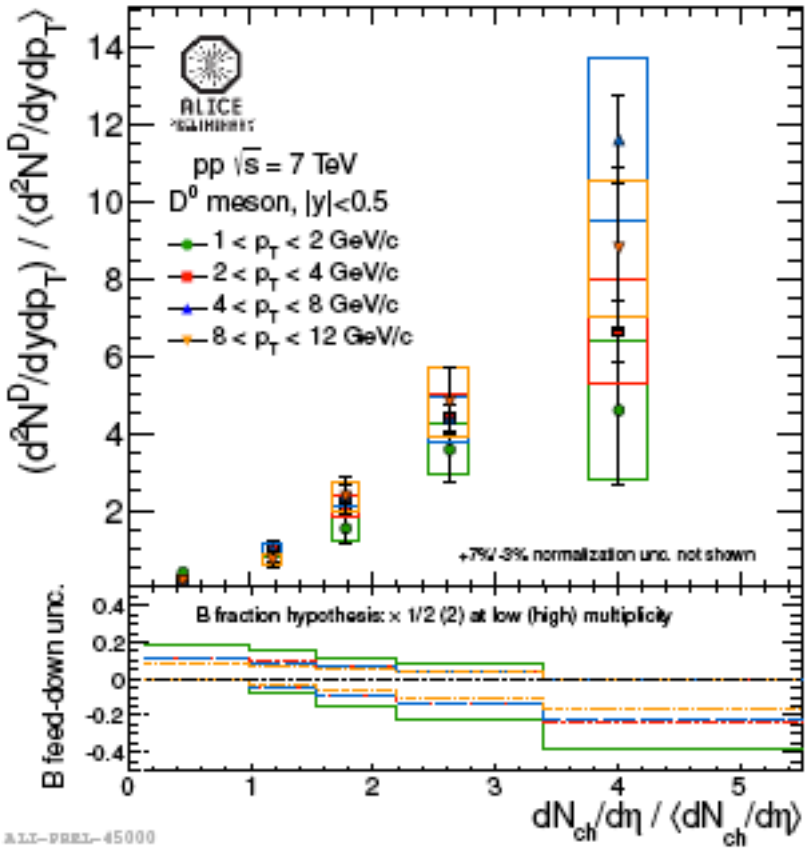
Summary

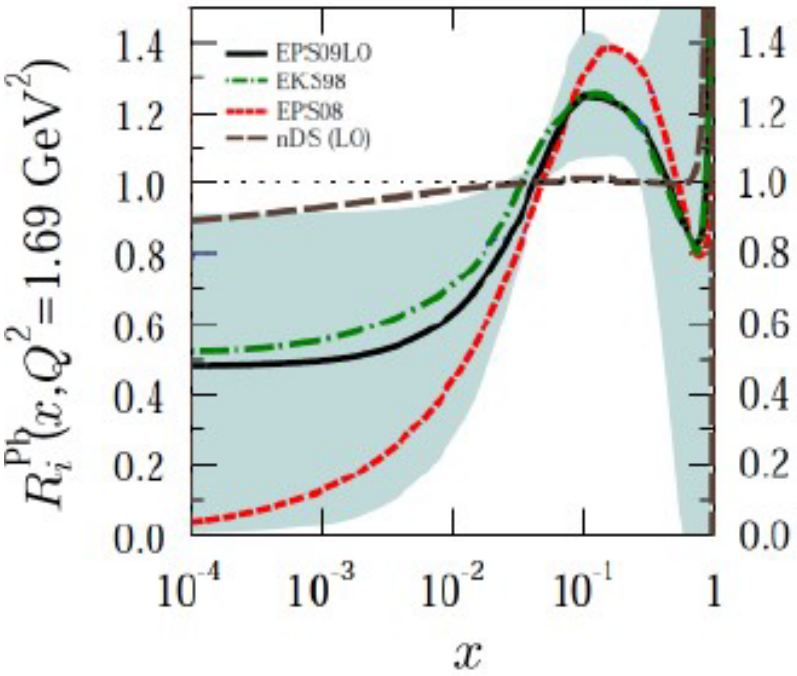
- Lots of new data from all facilities and many new theoretical developments
- Precision measurements needed to further constraint model calculations
- Many more exciting results ahead of us
  - LHC Run2 (mid 2015) and upgrades (2018)
  - Future electron-hadron collider
- Enjoy the conference!

Thank you

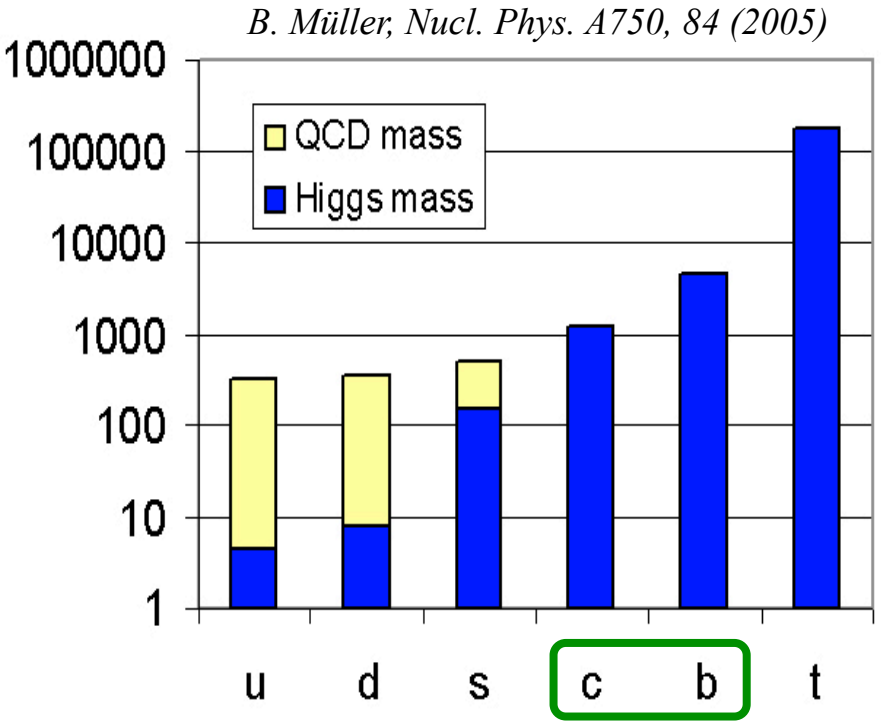
Backup


ATLAS
PYTHIA
HERWIG
POWHEG+PYTHIA
POWHEG+HERWIG
data with stat. uncertainty
stat. + syst. uncertainty
√s = 7 TeV, ∫Ldt = 0.30 pb⁻¹
25 < p_T < 30 GeV, |η| < 2.5
30 < p_T < 40 GeV, |η| < 2.5
40 < p_T < 50 GeV, |η| < 2.5
50 < p_T < 60 GeV, |η| < 2.5
60 < p_T < 70 GeV, |η| < 2.5
25 < p_T < 70 GeV, |η| < 2.5
R(p_T,z)/Δz
Data/Theory
z = p_T(D**)/E(jet)


ALICE
pp $\sqrt{s}$ = 7 TeV
D^0 meson, |y|<0.5
1 < p_T < 2 GeV/c
2 < p_T < 4 GeV/c
4 < p_T < 8 GeV/c
8 < p_T < 12 GeV/c
+7%/-8% normalization unc. not shown
$(d^2N^D/dydp_T) / \langle d^2N^D/dydp_T \rangle$
B fraction hypothesis: × 1/2 (2) at low (high) multiplicity
B feed-down unc.
$dN_{ch}/d\eta / \langle dN_{ch}/d\eta \rangle$
ALI-PREL-45000


EPS09LO
EKS98
EPS08
nDS (LO)
$R_i^{\mathrm{Pb}}(x,Q^2{=}1.69\ \mathrm{GeV}^2)$
x
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

Heavy quarks are ideal probes



- Charm and beauty quarks are 250-450 times heavier than light quarks
- They are abundantly produced at the LHC, **predominantly in the early phase of the collisions**
- **Production rates calculable in pQCD**

- Symmetry breaking
  - Higgs mass: electro-weak symmetry breaking → current quark mass
  - QCD mass: chiral symmetry breaking → constituent quark mass

- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

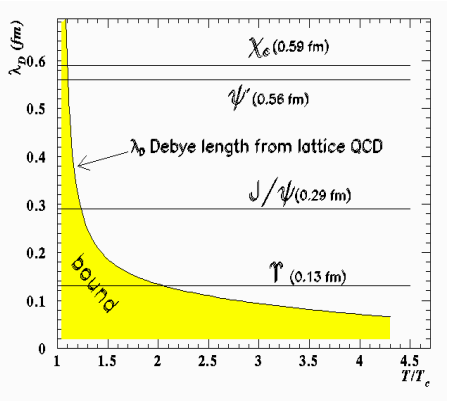
- Test QCD at transition from perturbative to non-perturbative regime: charm and beauty quarks provide hard scale for QCD calculations

Quarkonia production in hot QCD matter

- Colour screening length λ_D in the deconfined medium decreases with temperature

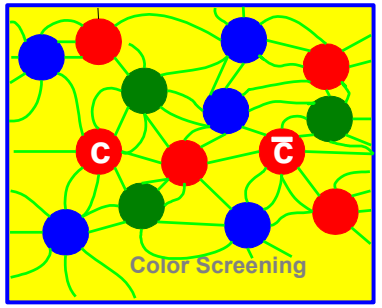
- Quarkonia "melt" when their binding distance becomes bigger than screening length → yields suppressed (one of the first QGP signatures)

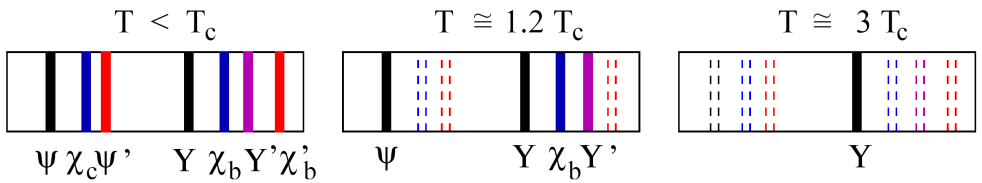
T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416



- Screening at different temperature for different states (binding energy) → sequential suppression of the quarkonium states → QCD thermometer

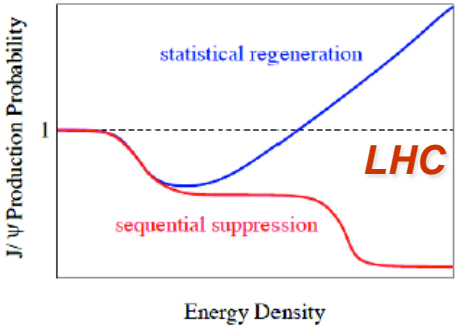
S. Digal, P. Petreczky and H. Satz, Phys. Rev. D 64 (2001) 0940150





- Enhancement via (re-)generation of quarkonium states due to large heavy quark multiplicity

A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Phys. Lett. B 571(2003) 36



Experiment	Heavy flavor	Quarkonia	Electroweak
PHENIX	μ: 1.2<|y|<2.2 e: |y|<0.35	J/ψ, $\Upsilon\rightarrow\mu\mu$ J/ψ, $\Upsilon\rightarrow$ee	γ, di-electron
STAR	e, D: |y|<1	J/ψ, $\Upsilon\rightarrow$ee	di-electron
ALICE	μ: 2.5<|y|<4 e,D: |y|<0.9 B$\rightarrow$J/ψX$\rightarrow$eeX	J/$\psi\rightarrow\ \mu\mu$ J/$\psi\rightarrow$ ee	γ
ATLAS	μ: |y|<1.05, p_T>4 GeV/c		γ: |y|<1.3, E_T (45-200 GeV) W$\rightarrow\mu\nu$: $\|\eta^{\mu}\|$<2.7,$p_T(\mu)$>7 GeV/c Z$\rightarrow\mu\mu$ (ee): |y|<2.7 (|y|<2.5)
CMS	B$\rightarrow$J/ψX$\rightarrow\mu\mu$X	J/$\psi\rightarrow\mu\mu$: |y|<2.4, p_T>6.5 GeV/c $\Upsilon\rightarrow\mu\mu$ |y|<2.4	γ: |y|<1.44, E_T (20-80 GeV) W$\rightarrow\mu\nu$: $\|\eta^{\mu}\|$<2.1,$p_T(\mu)$>25 GeV/c Z$\rightarrow\mu\mu$: |y|<2.1