Heavy-Ion Reactions: Selected Topics

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Excellence Cluster "Universe" - TU München

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Nuclear Physics in Bormio
Pre-Conference School
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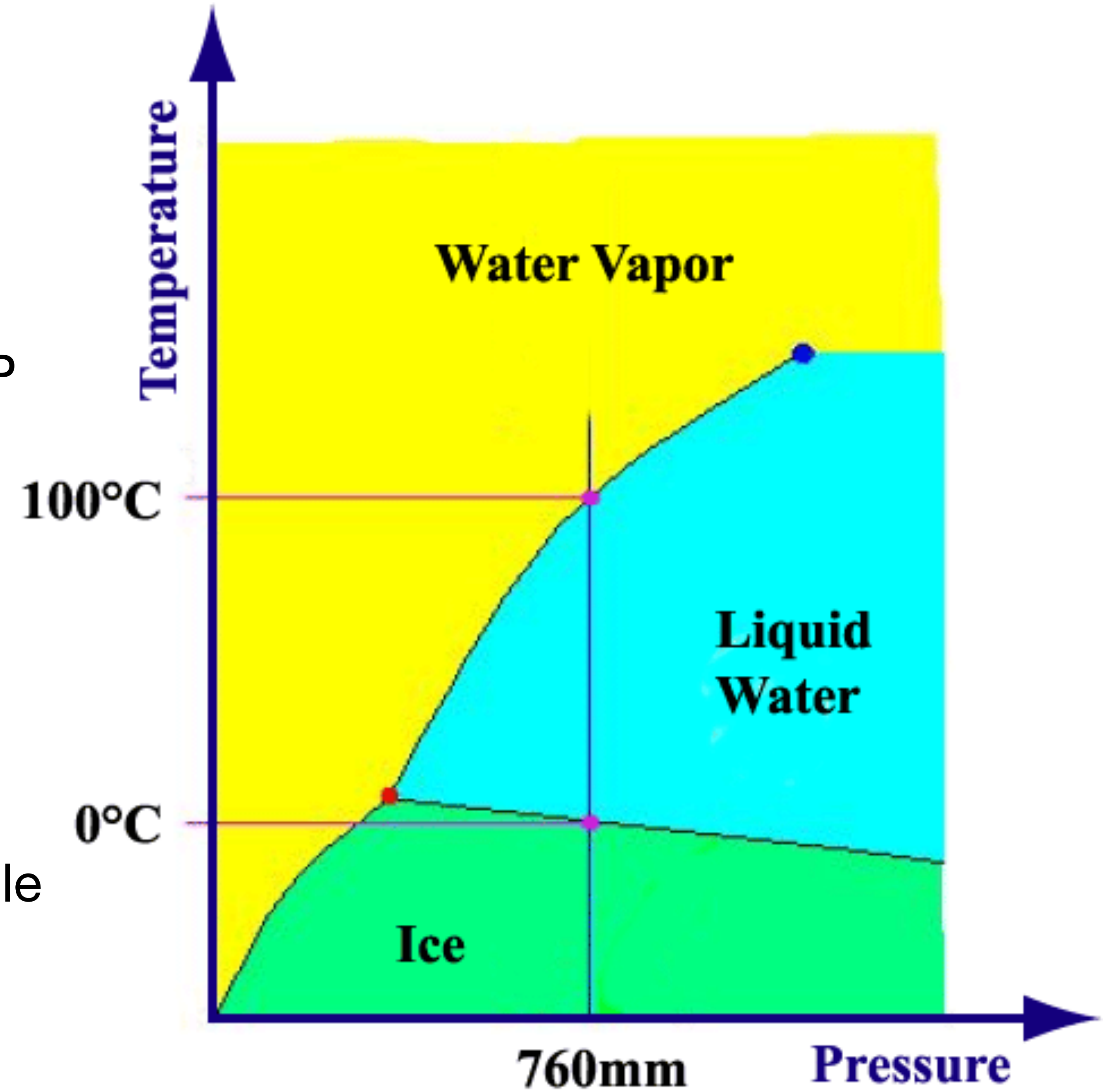
Technische Universität München

Basic Questions

- What happens to matter if you
  - heat it?
  - compress it?

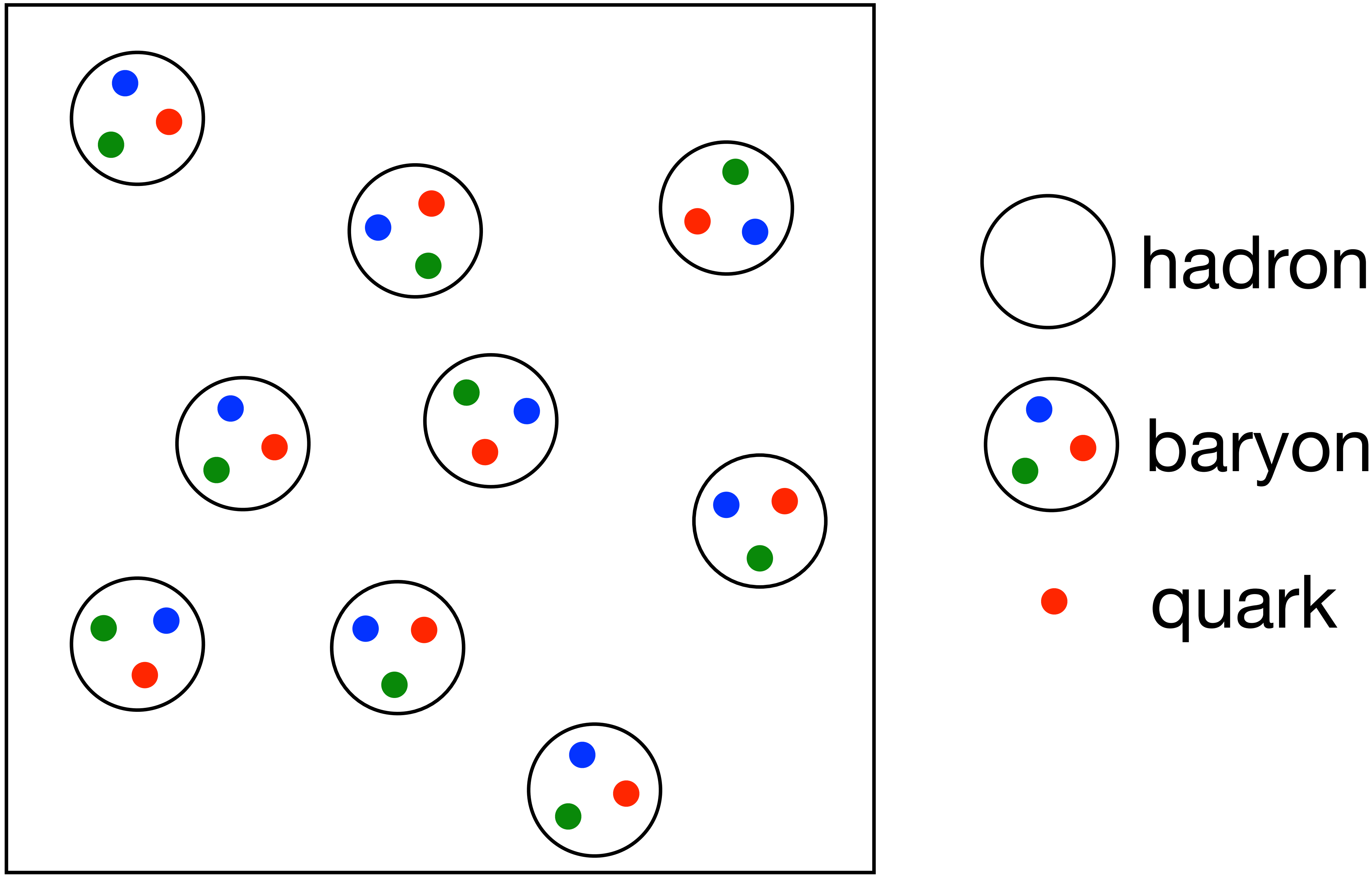
- With increasing temperature
  - solid → liquid → gas → plasma → QGP

- Emergent phenomena
  - hard to determine the properties of matter from the known properties of its constituents
  - e.g. ice, water, steam from H_2O molecule



- Matter properties:
  - temperature, viscosity, equation of state, degrees of freedom

Compressing Nuclear Matter



- Normal nuclear matter density: $$\rho_0 = \frac{A}{4\pi/3\, R^3} = \frac{1}{4\pi/3\, r_0^3} \approx 0.16\,\mathrm{fm}^{-3}$$
  - with r_0 = 1.15 fm

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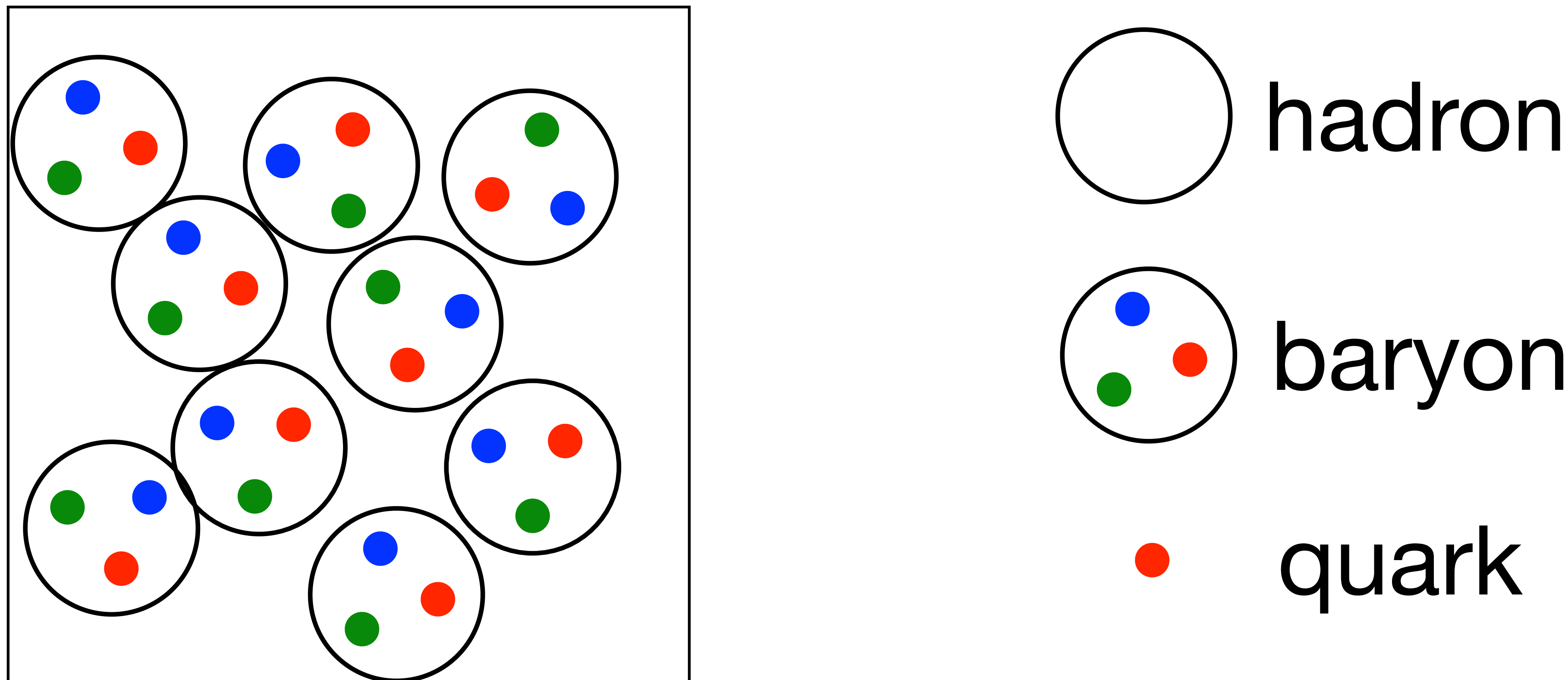

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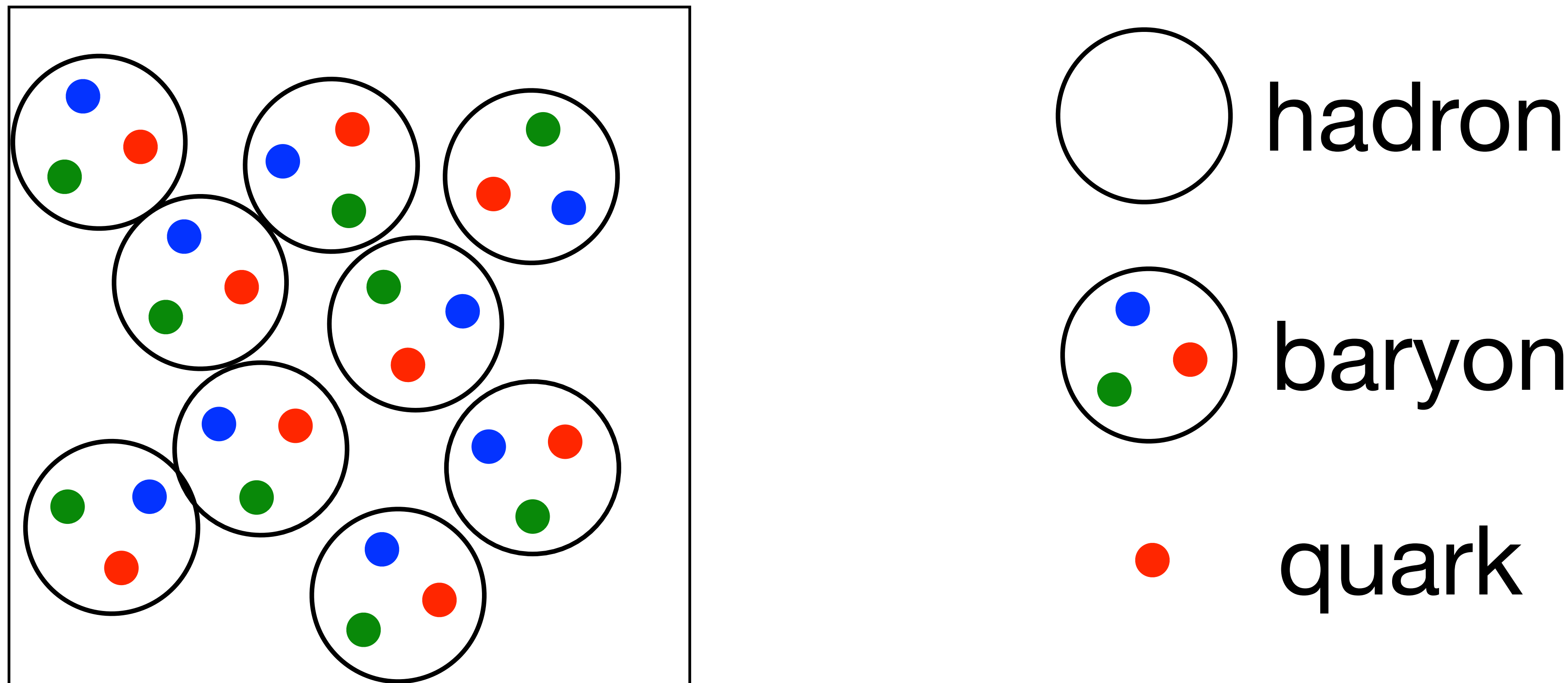

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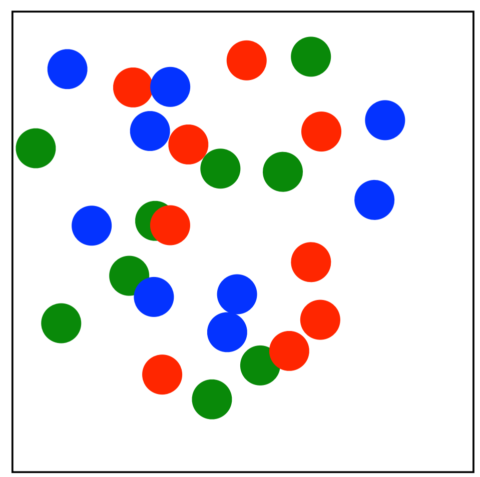
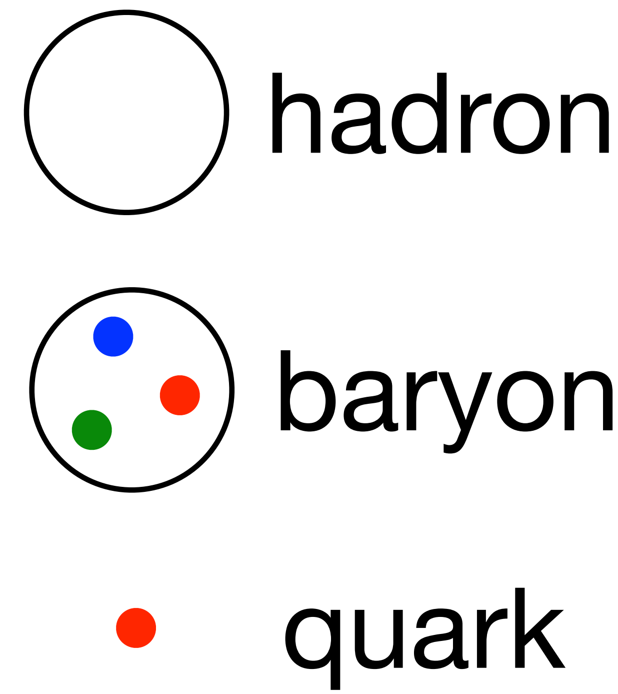
- Compressing nucleons:
  - (charge radius $r_n = 0.8$ fm)
  - nucleons will eventually start to overlap at a critical density
  - will see later that the actual value is $4\rho_0$

$$\rho_c = \frac{1}{4\pi/3\,r_n^3} \approx 0.47\,\mathrm{fm}^{-3} = 3\rho_0$$

Compressing Nuclear Matter





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The First QCD Phase Diagram

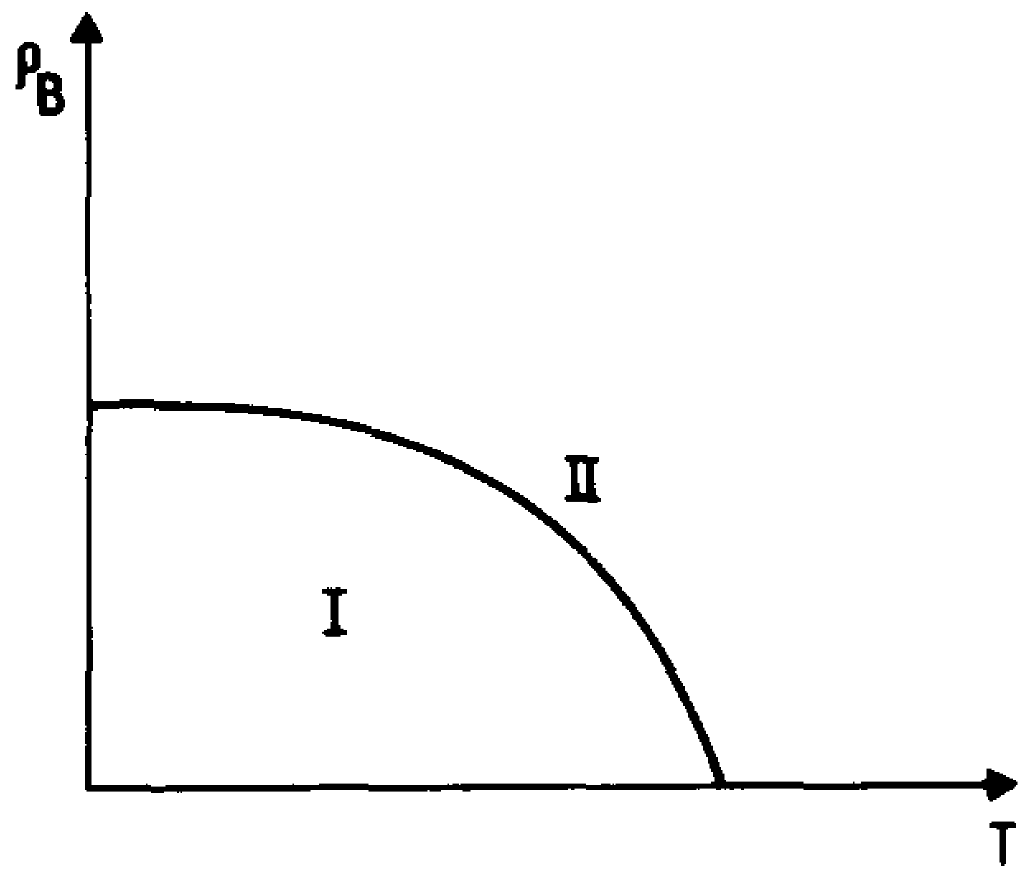
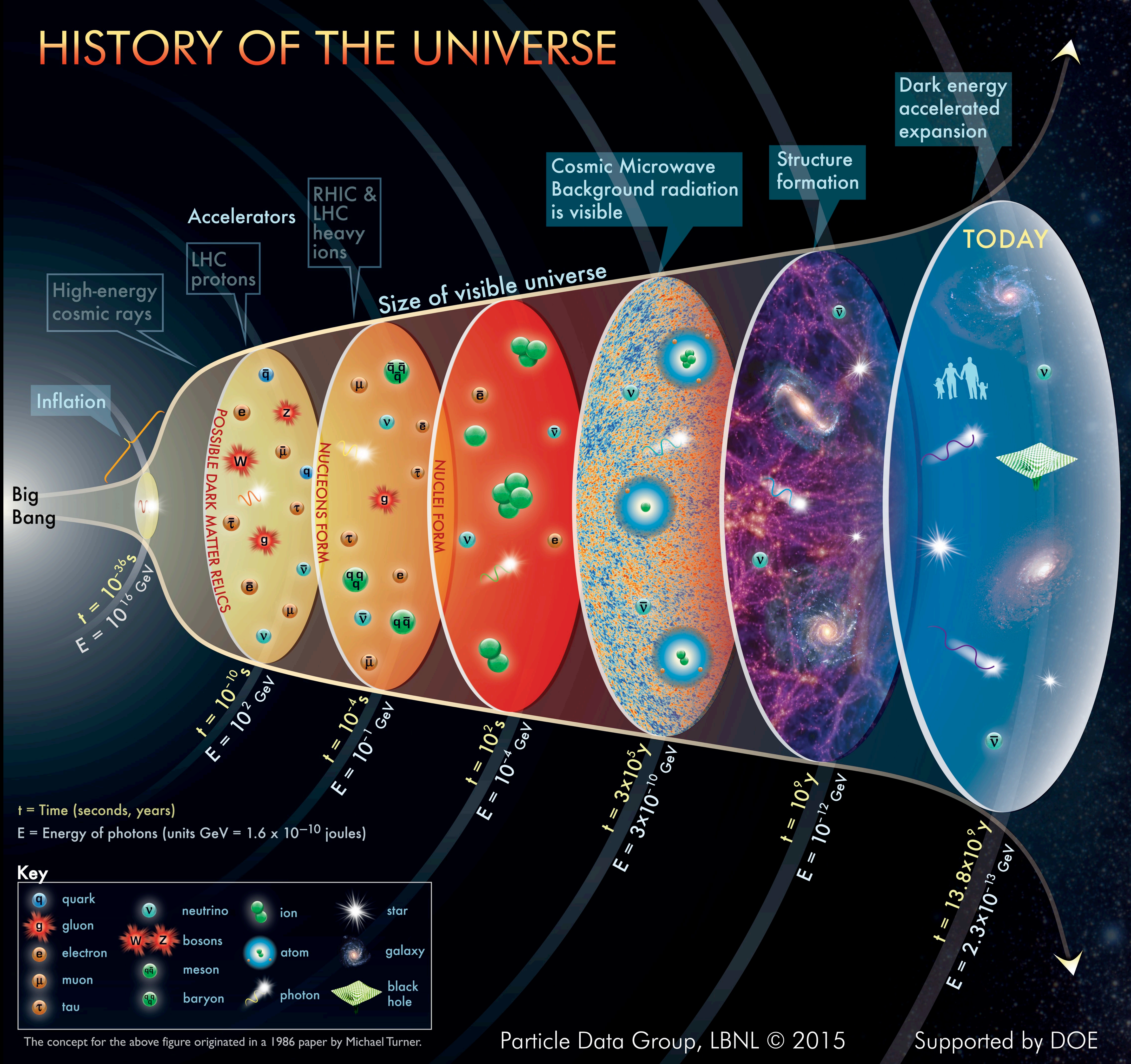


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

- At low temperature and density (phase I)
  - confinement & chiral symmetry spontaneously broken
- At high temperature and/or density (phase II)
  - deconfinement
  - new state of strongly interacting matter

N. Cabibbo and G. Parisi, PLB 59 (1975) 67
J. C. Collins and M. J. Perry, PRL 34 (1975) 1353


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
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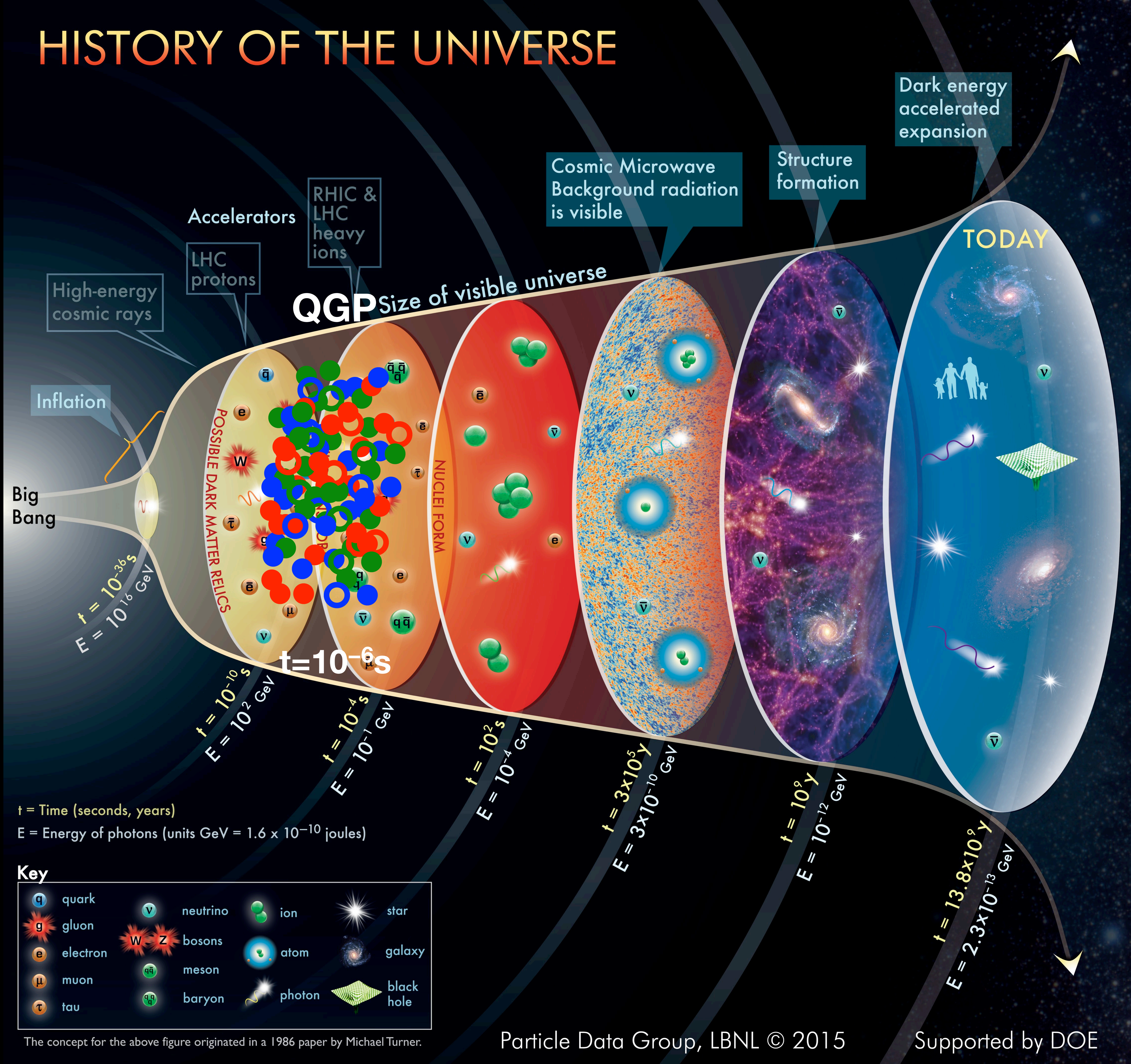
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POSSIBLE DARK MATTER RELICS
NUCLEI FORM
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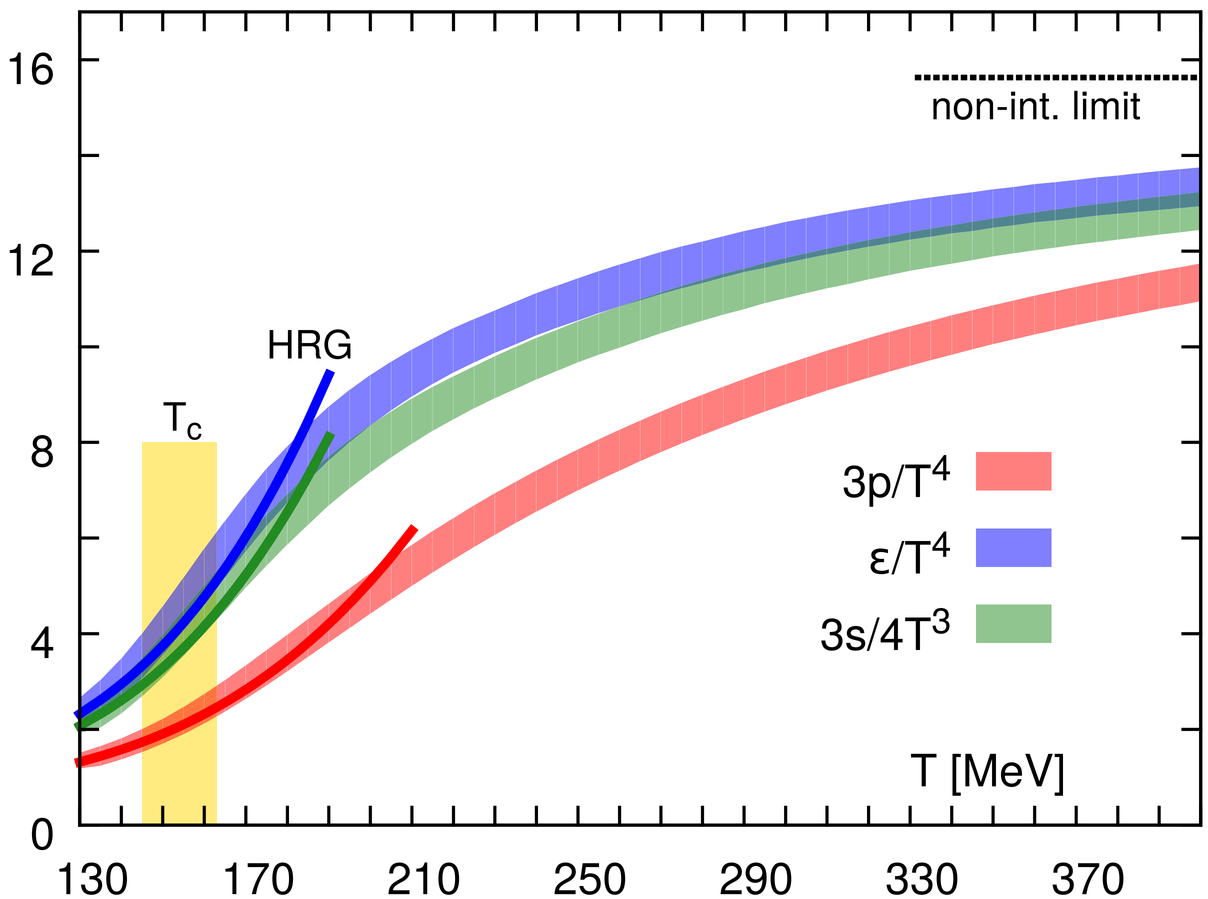
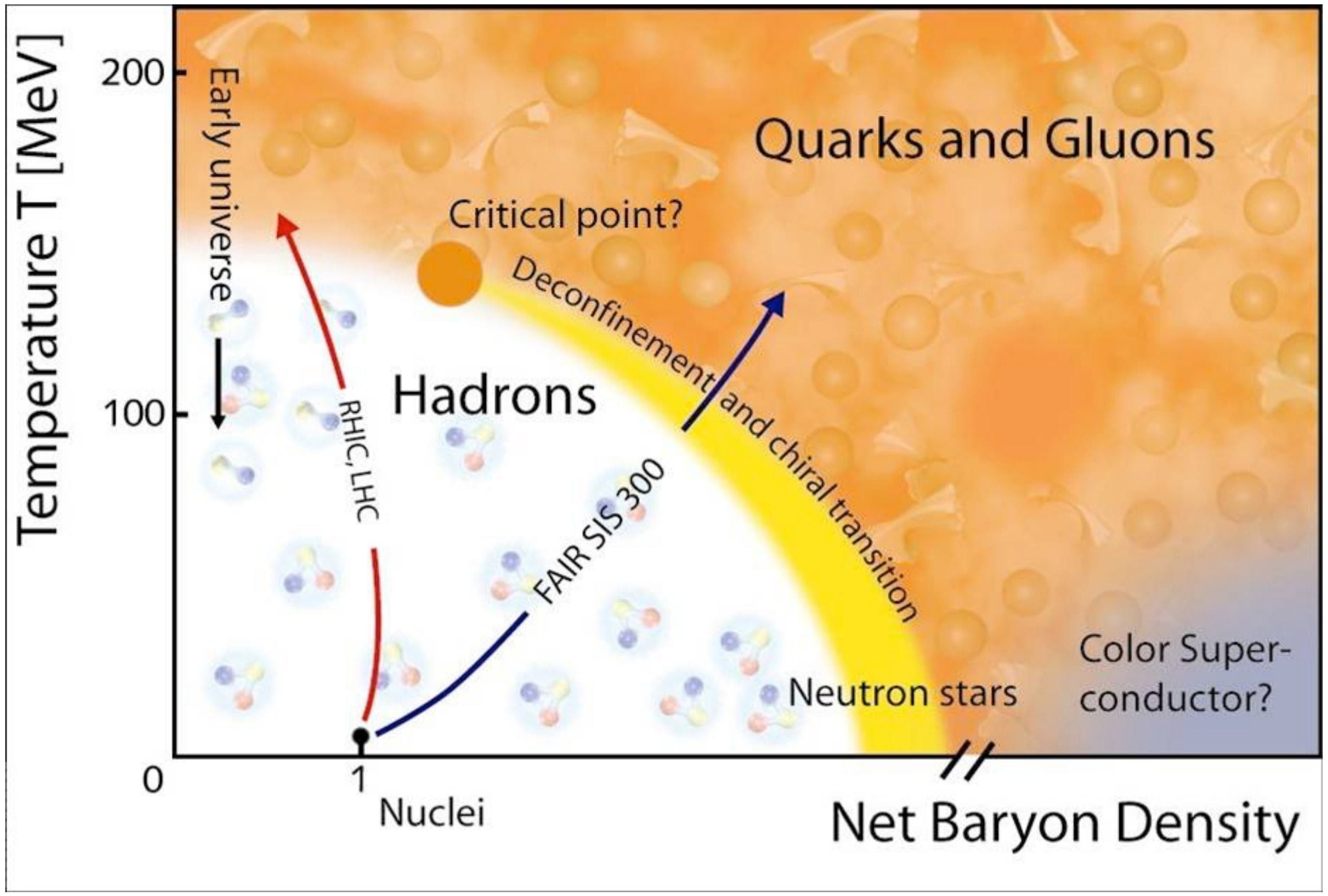
Phases of QCD Matter

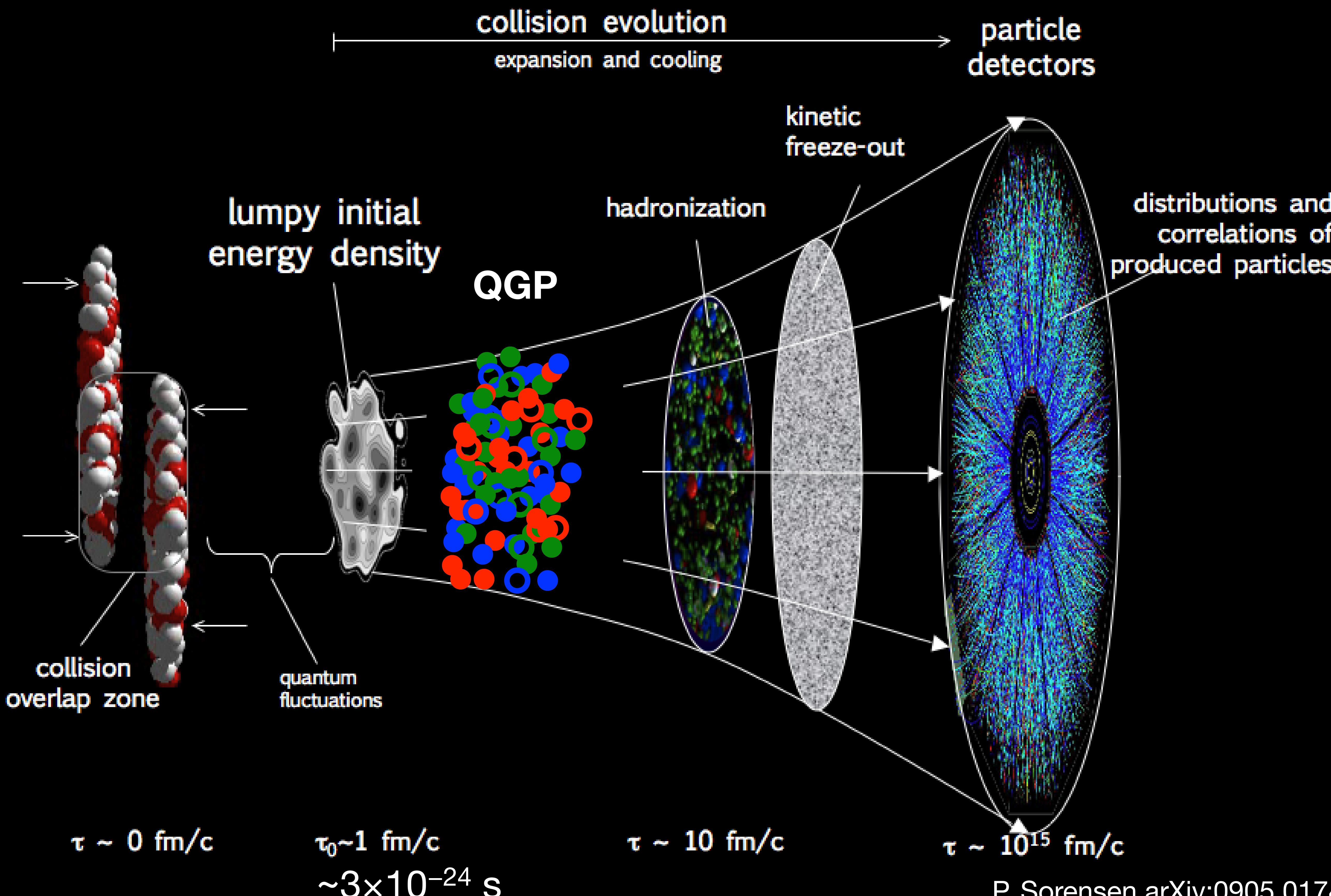


Wuppertal-Budapest, JHEP 09 (2010) 073
HotQCD, PRD 90 (2014) 094503



- Phase transition at $T_c = 154 \pm 9$ MeV
  - 1 MeV ~ 10^{10} K → $T_c = 2 \times 10^{12}$ K
- Centre of the sun: 2×10^7 K
- The QGP is more than 100 000 times hotter than the centre of the sun

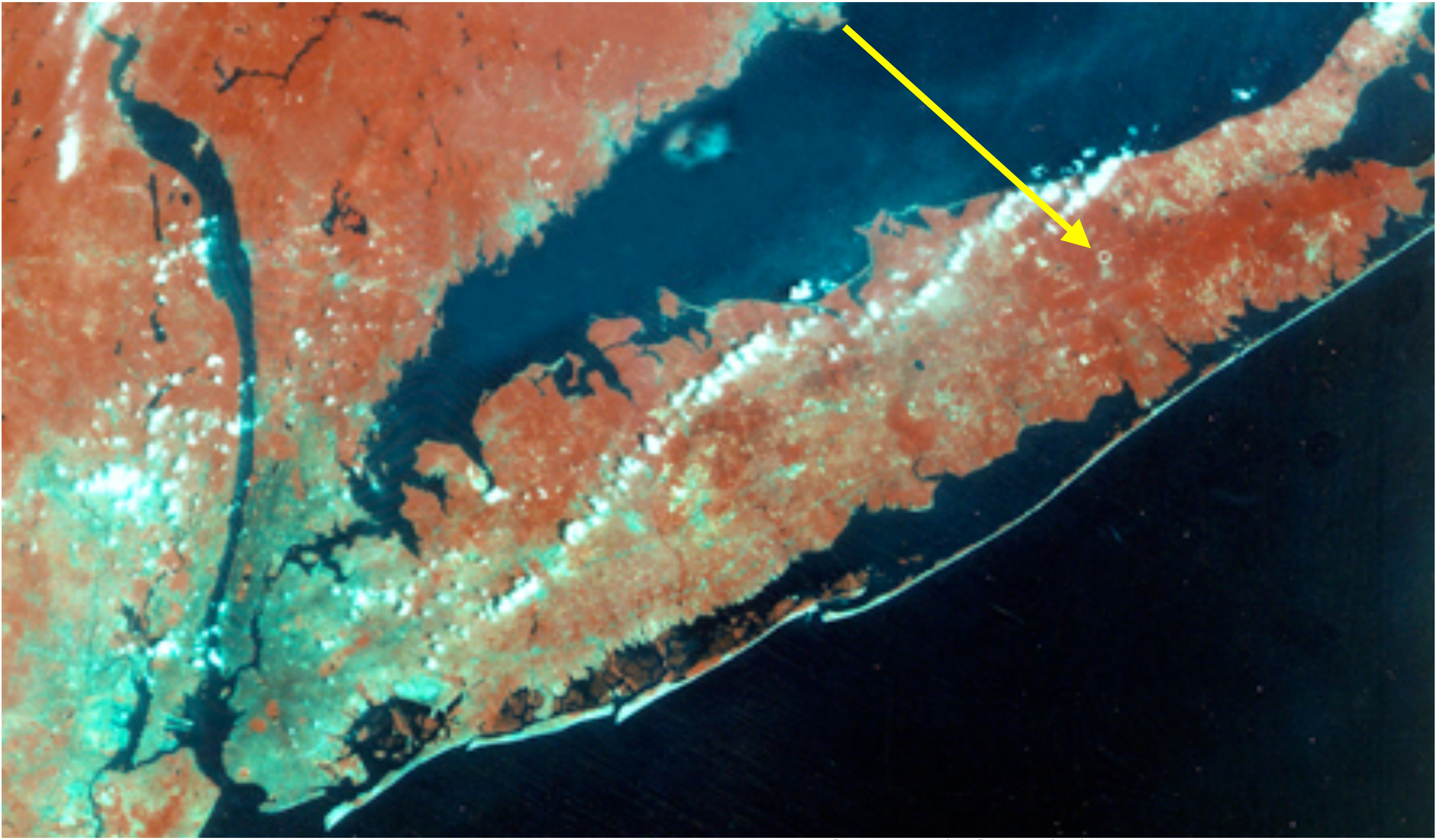
Nuclear collisions and the QGP expansion

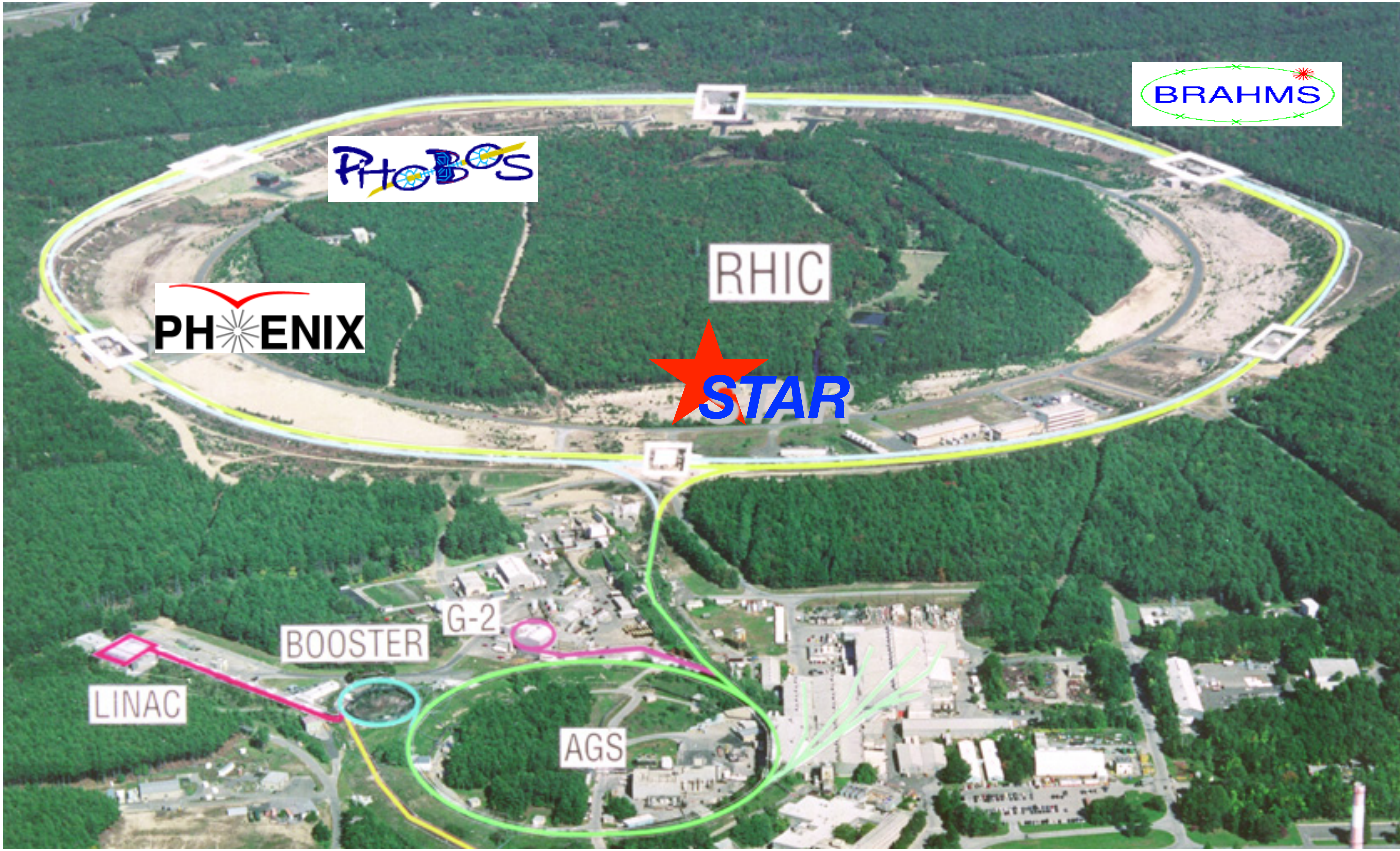


P. Sorensen arXiv:0905.0174

RHIC at BNL

Relativistic Heavy Ion Collider at Brookhaven National Lab





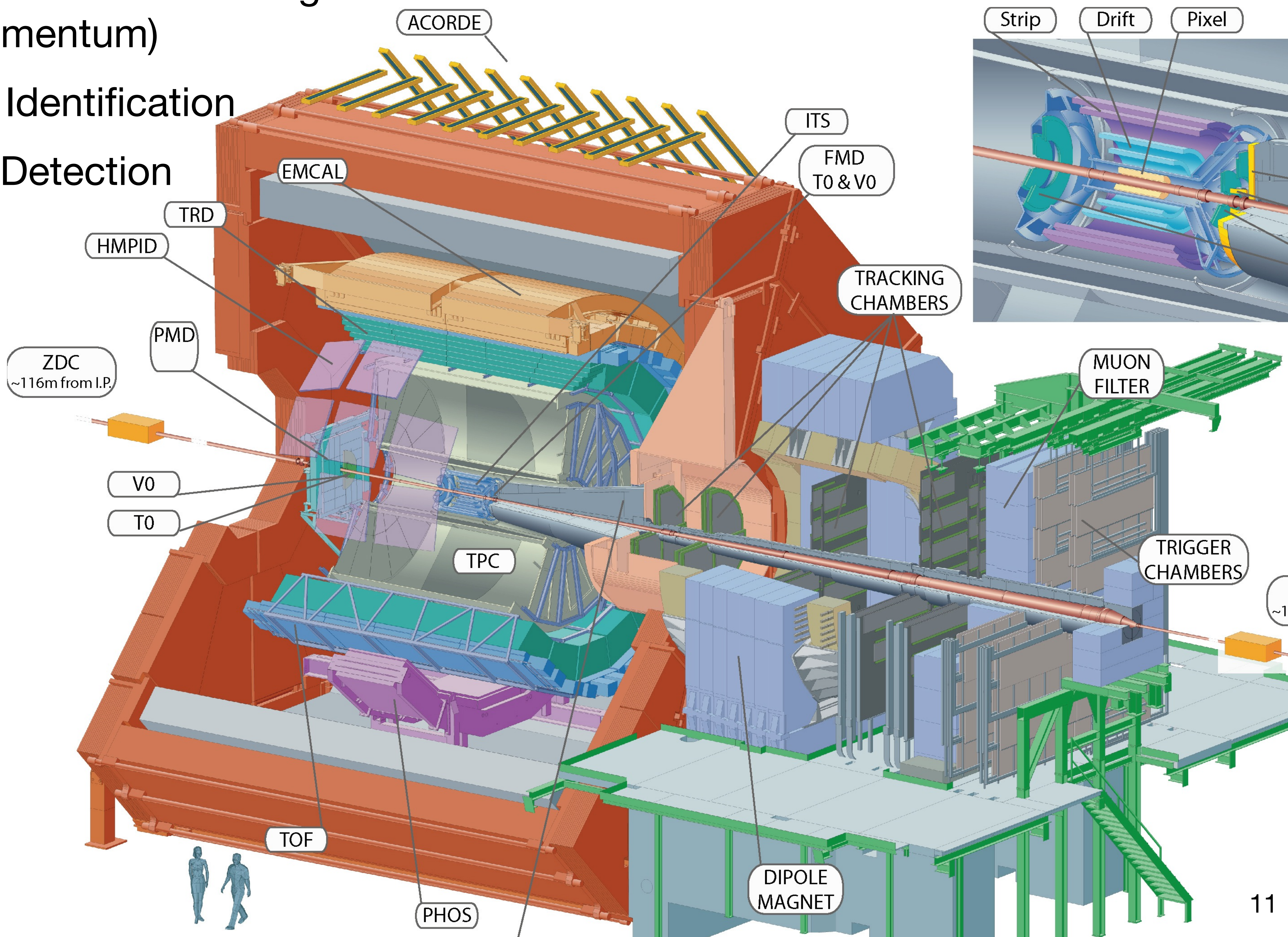
- Relativistic Heavy Ion Collider
    - 3.83 km circumference, 2 independent rings, superconducting magnets
    - p+p: $\sqrt{s} \leq 500$ GeV (polarized beams), A+A: $\sqrt{s_{NN}} \leq 200$ GeV (A = d, Cu, Au, U)

The Large Hadron Collider

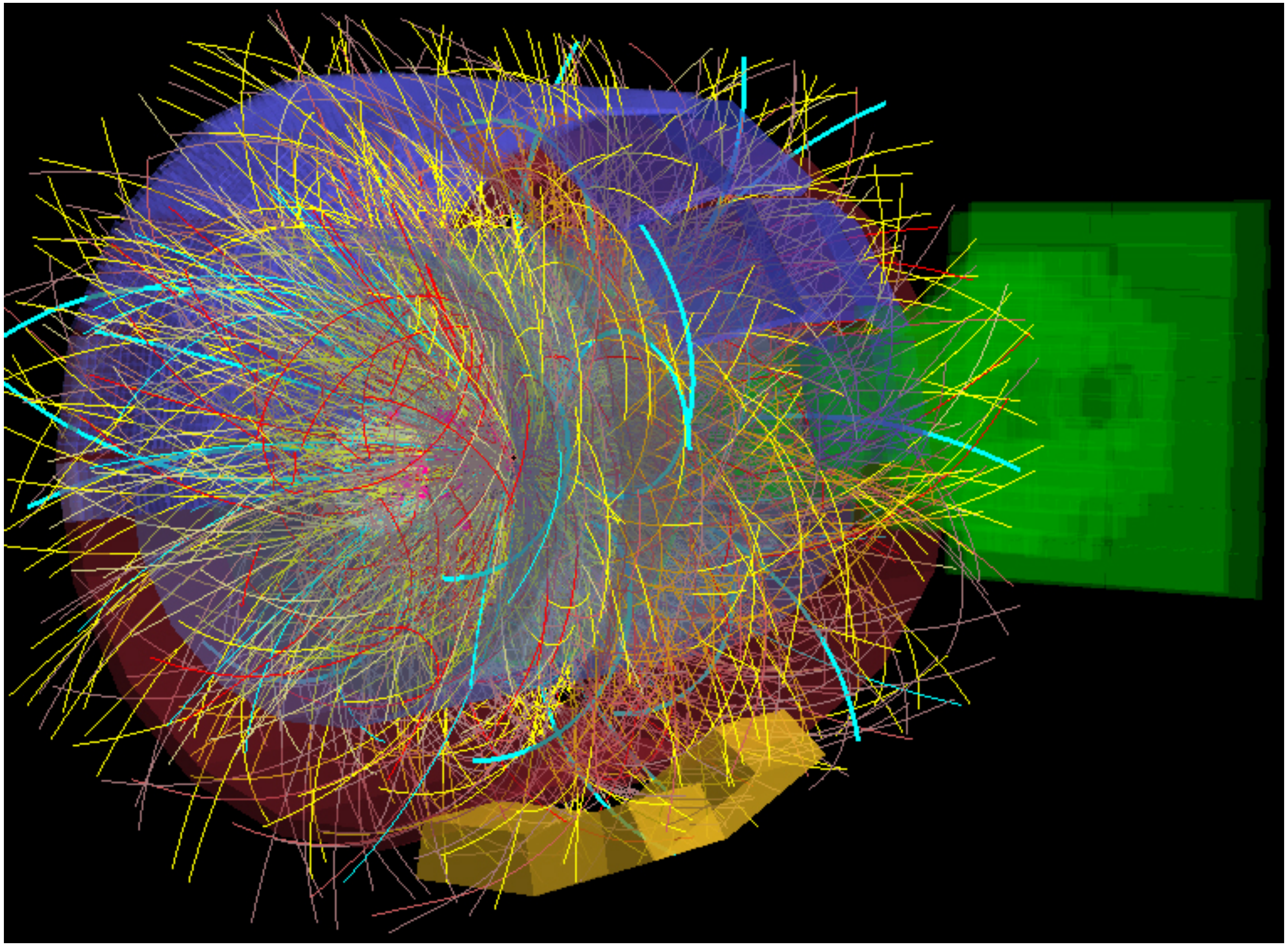
- 27 km circumference
- superconducting magnets (8 T)
- up to 100 m below ground
- pp: $\sqrt{s}$ = 0.9, 2.36, **2.76, 5.02**, 7, 8, 13 TeV (top: 14 TeV)
- pPb: $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV (top: 8.8 TeV)
- Pb–Pb: $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV (top: 5.5 TeV)

A Large Ion Collider Experiment

- Charged Particle Tracking (low momentum)
- Particle Identification
- Photon Detection



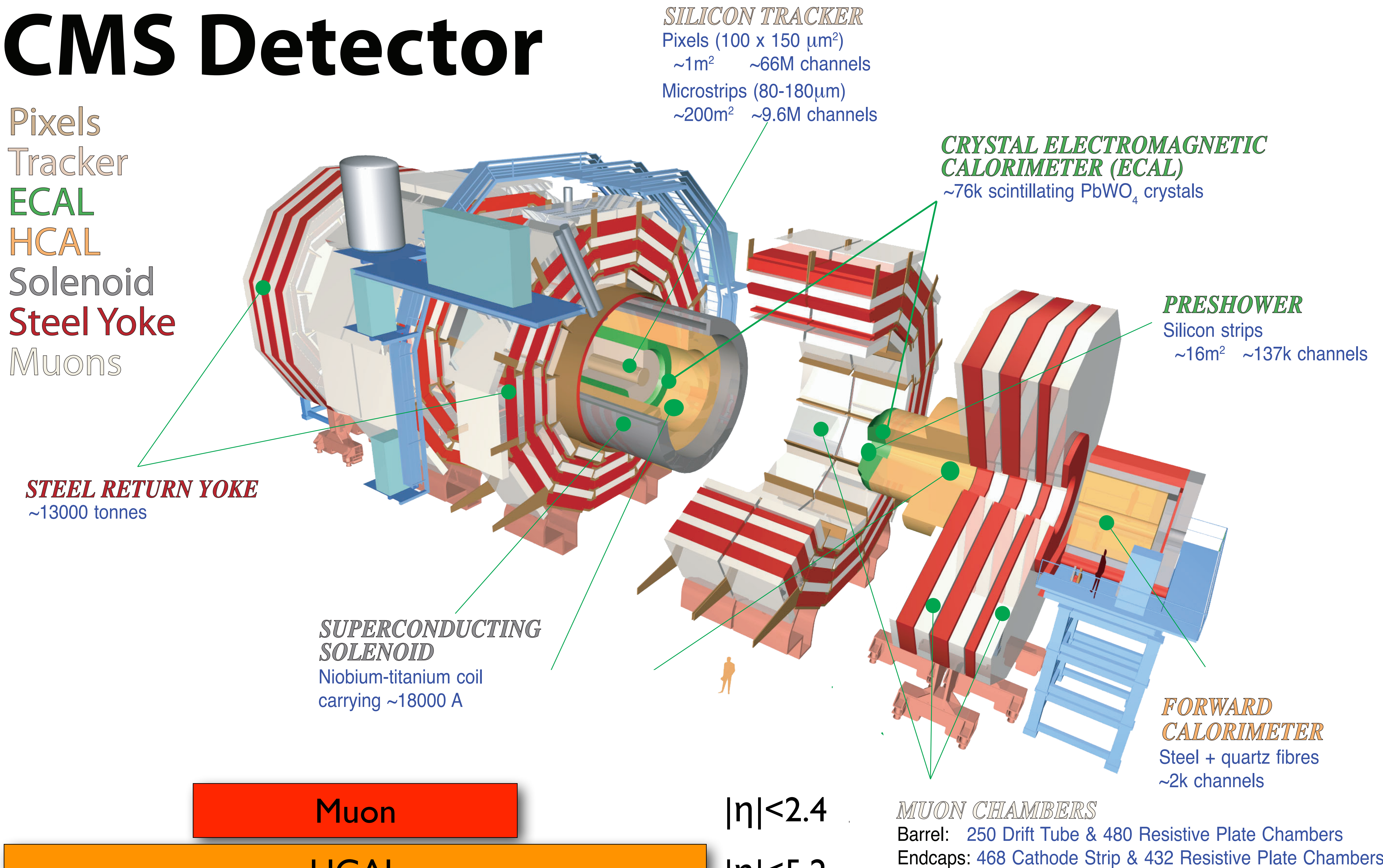
Heavy-Ion Collision in ALICE

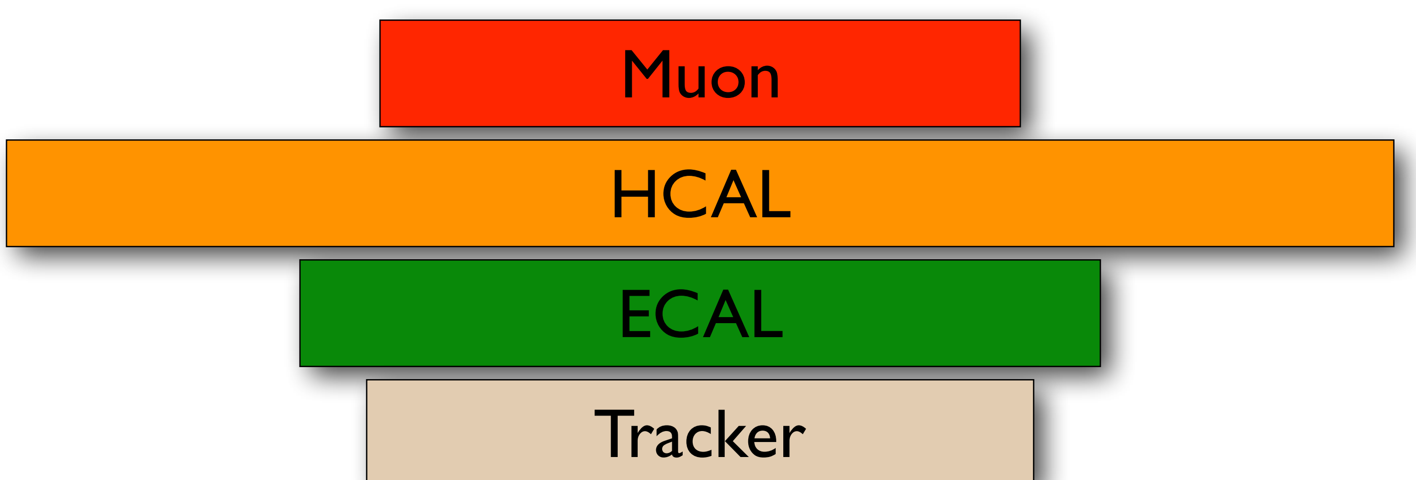


- A central Pb–Pb collision produces ~18000 charged particles
  - at midrapidity: 1800 per unit rapidity

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

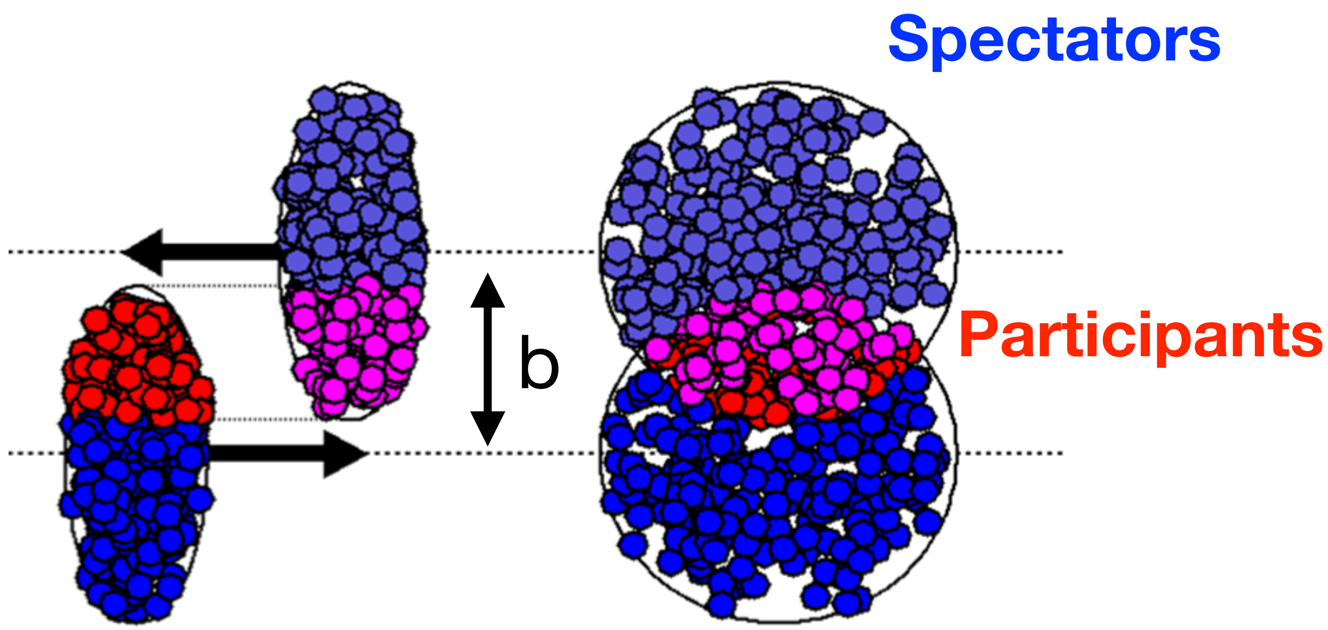




Muon	$\|\eta\|<2.4$
HCAL	$\|\eta\|<5.2$
ECAL	$\|\eta\|<3.0$
Tracker	$\|\eta\|<2.5$

Centrality: N_{part} and N_{coll}

- Centrality of a collision:
  - "impact parameter" b
  - N_{coll}: number of inelastic nucleon-nucleon collisions
  - N_{part}: number of nucleons undergoing at least one inelastic nucleon-nucleon collision



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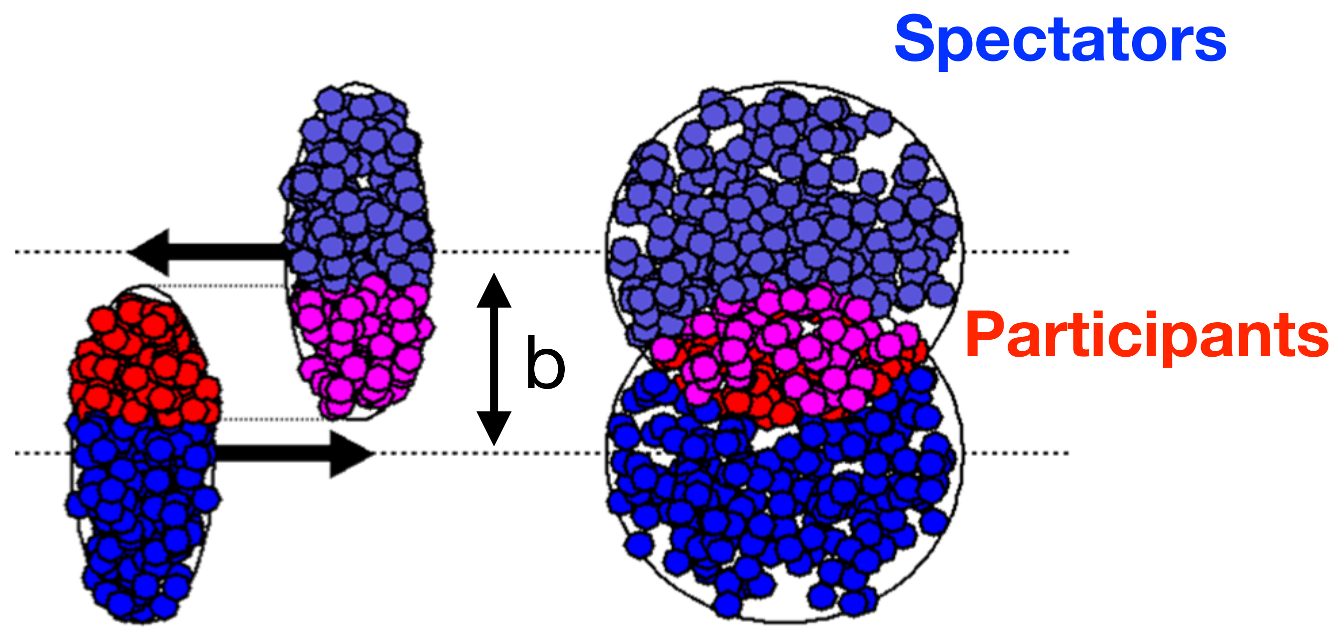

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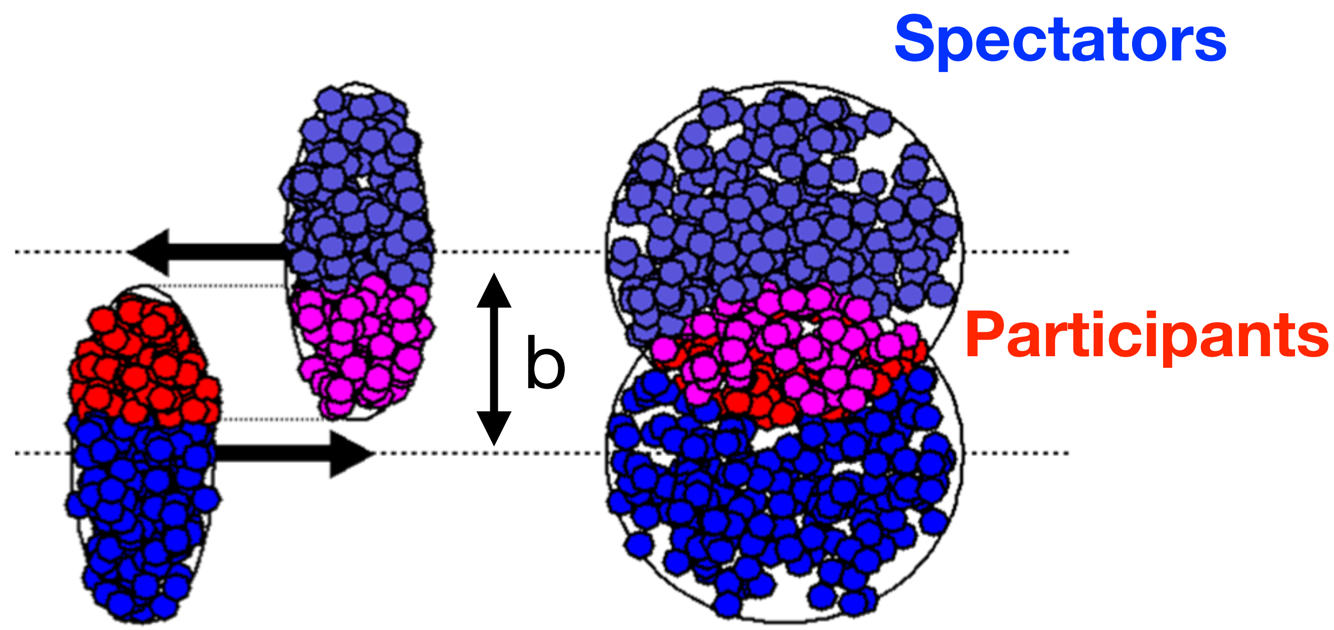

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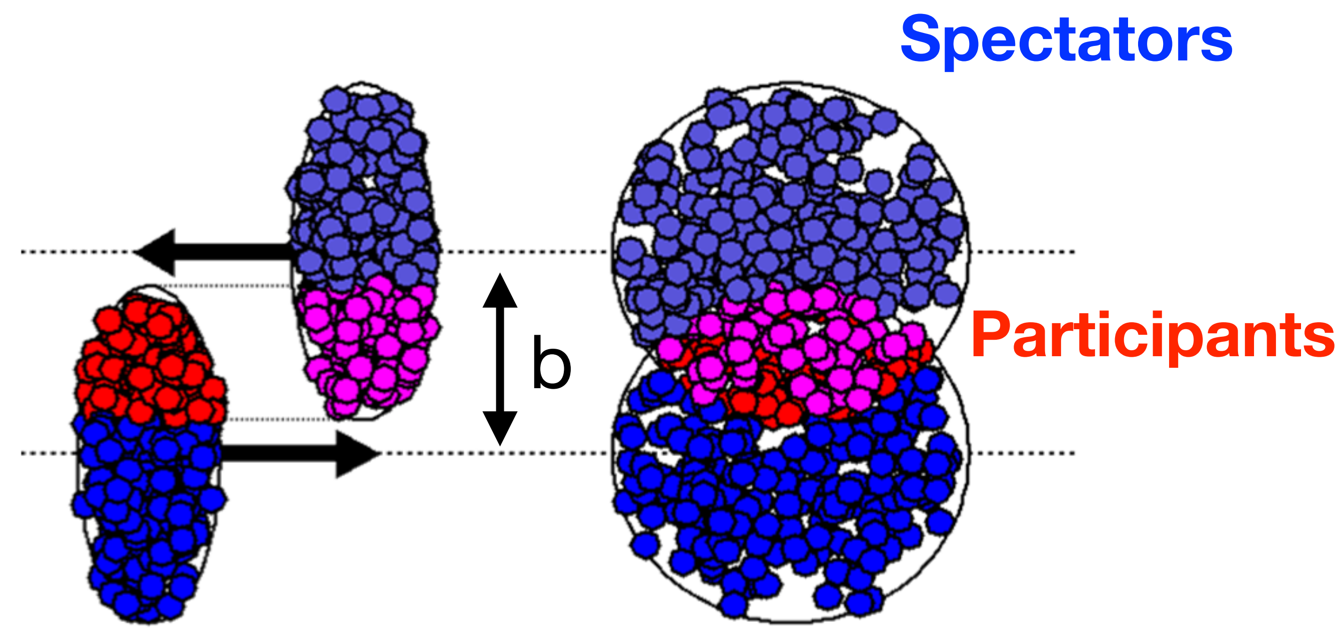

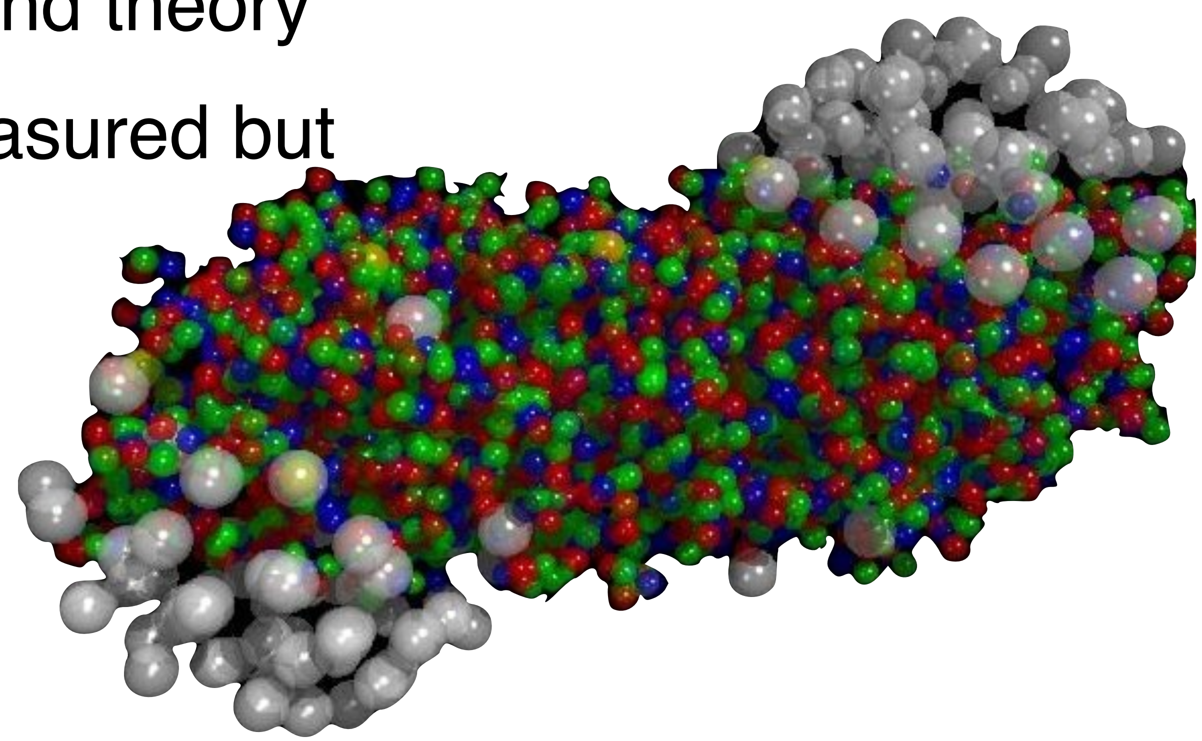

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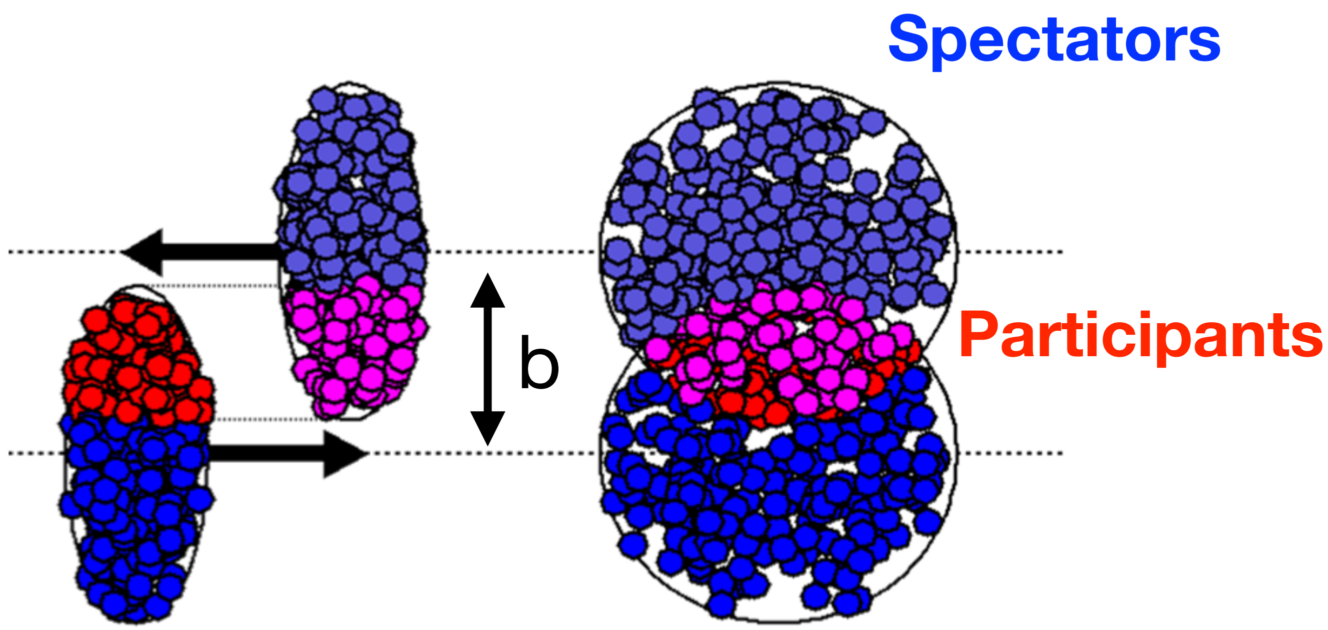

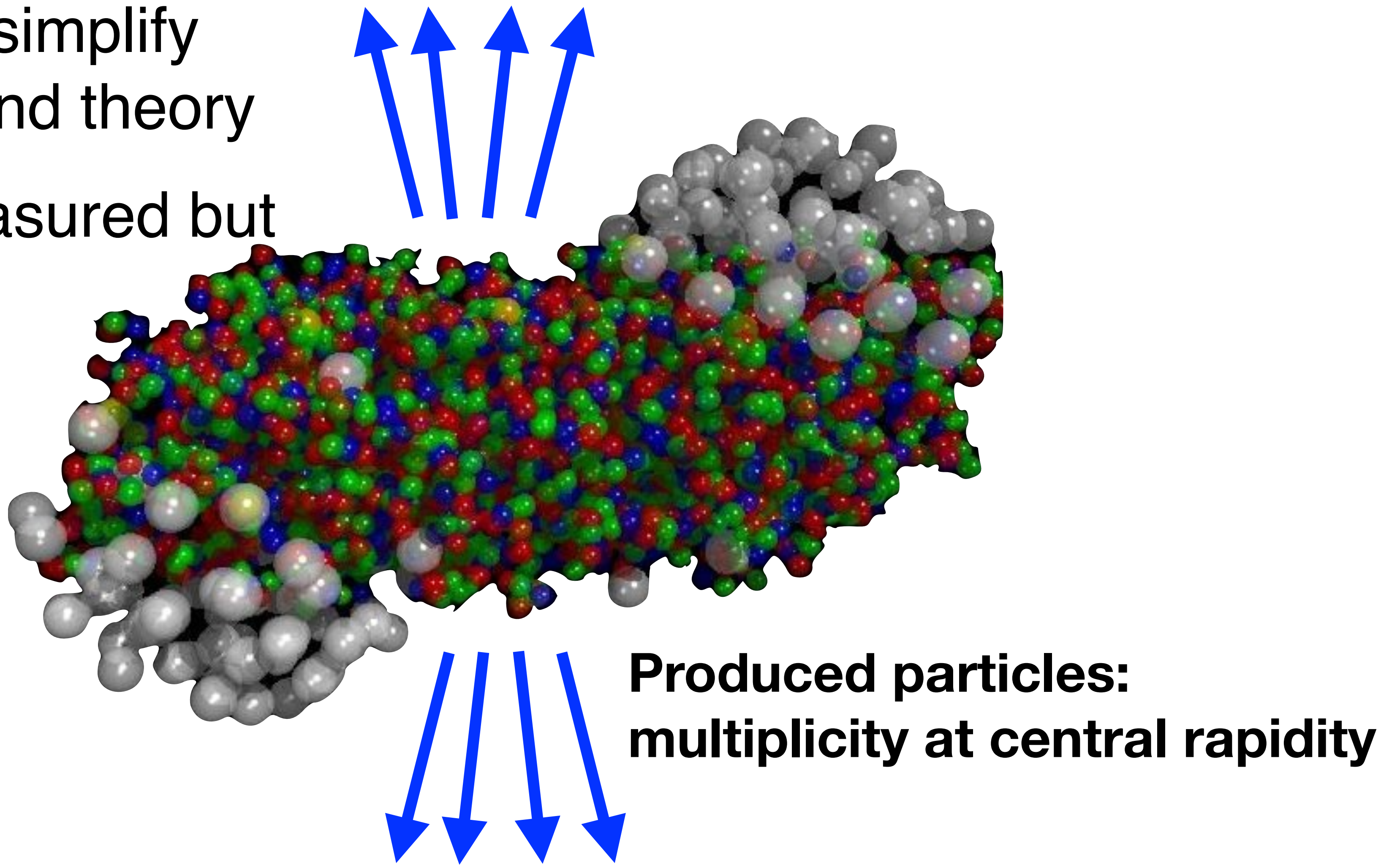

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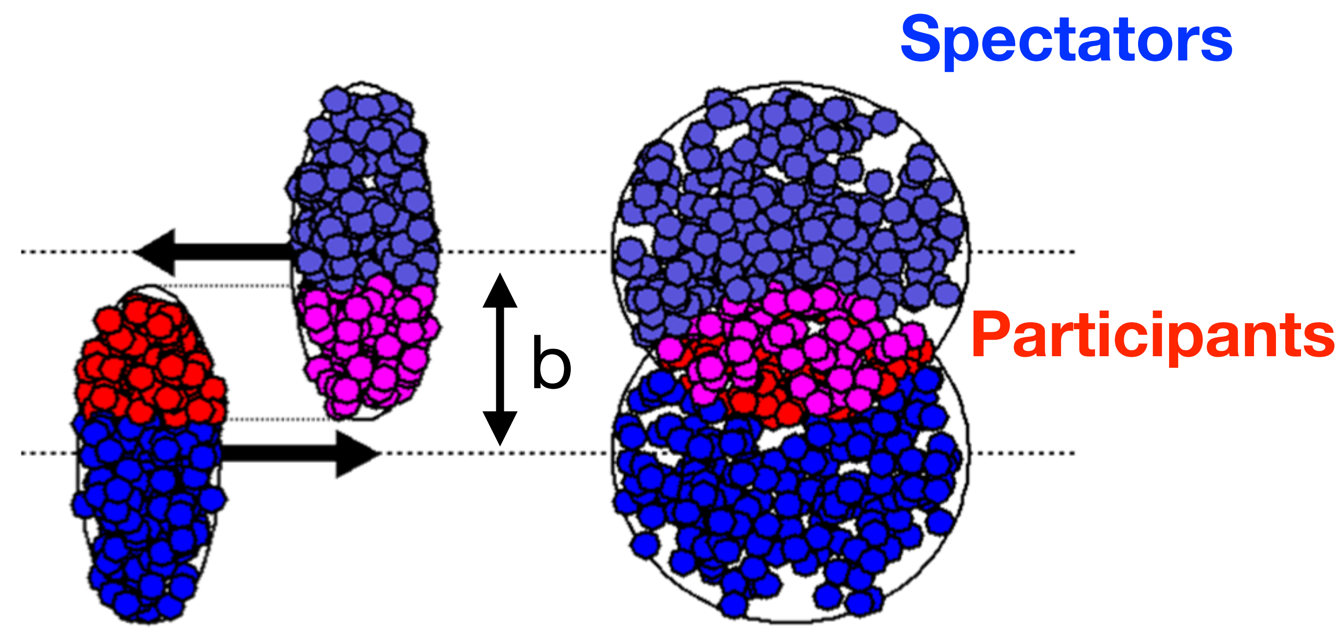

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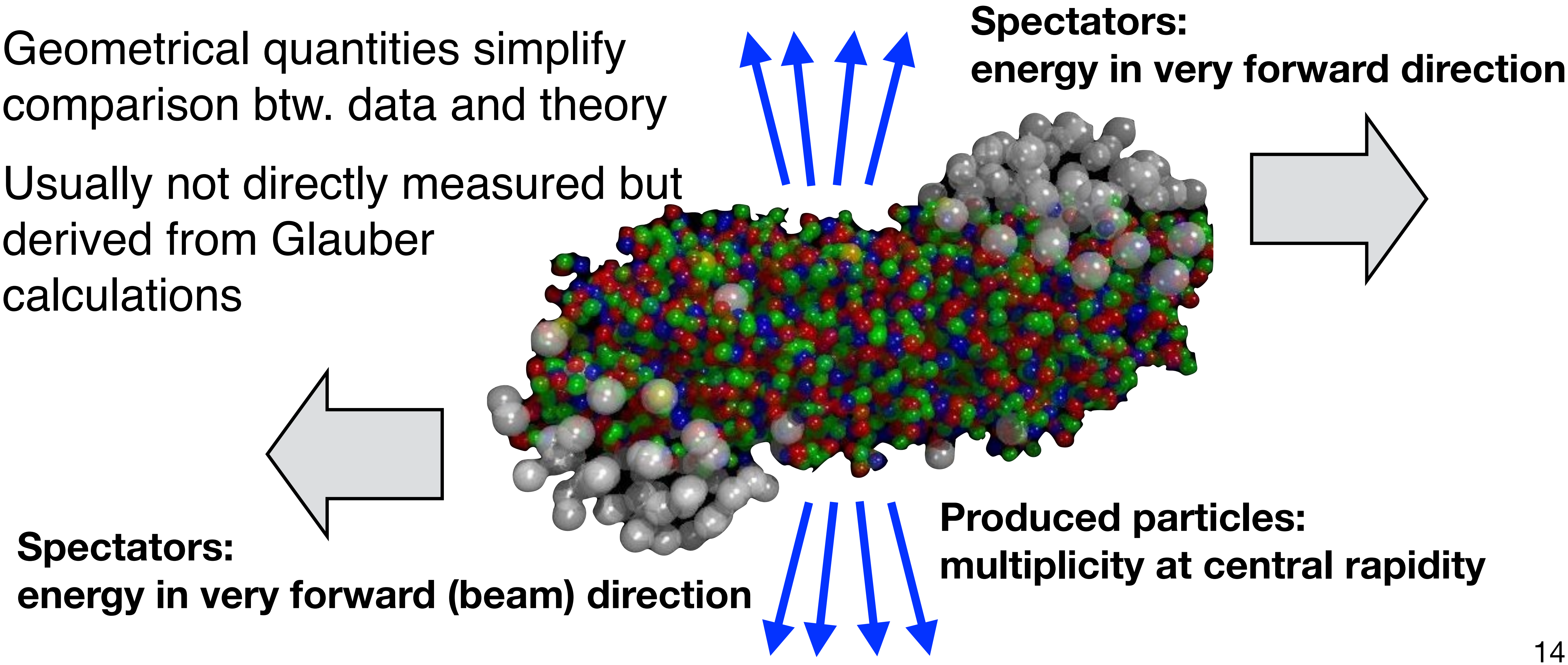
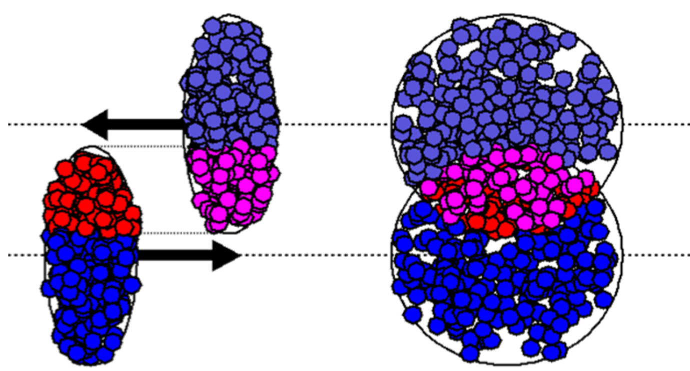
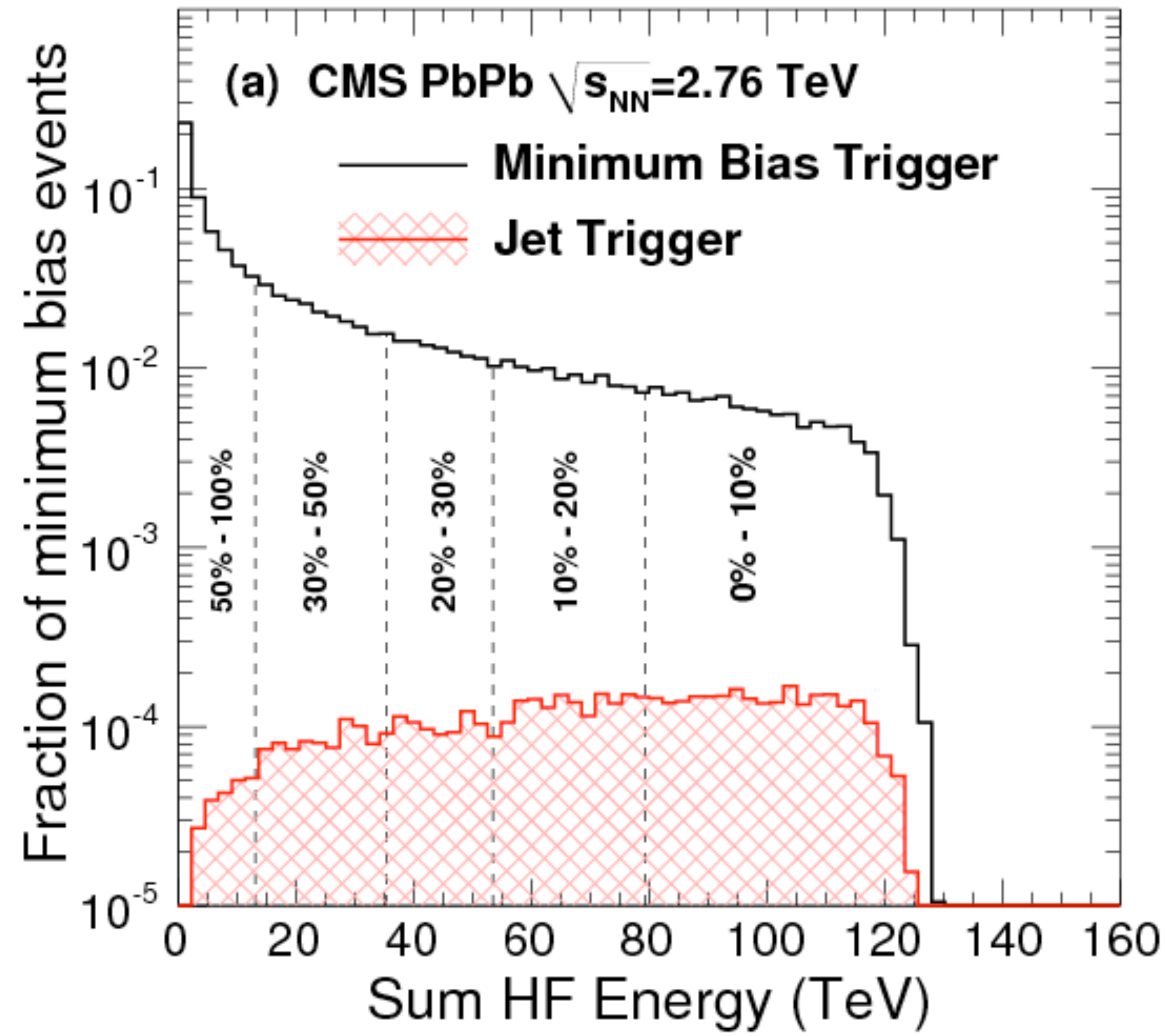


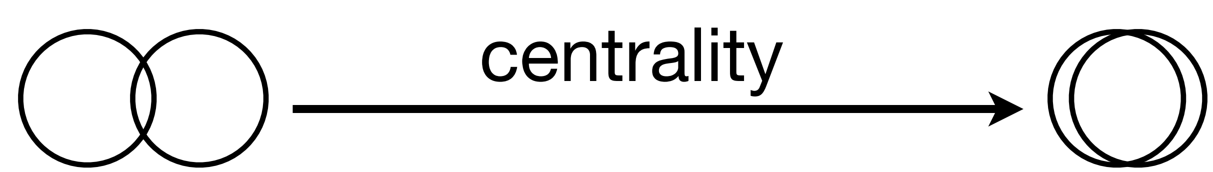
Determining Centrality

- Collision centrality (overlap of the nuclei) related to the energy deposit in forward calorimeters
- Relate to geometrical quantities with a Glauber MC model
  - N_{part} = number of participating nucleons



  - N_{coll} = number of binary collisions

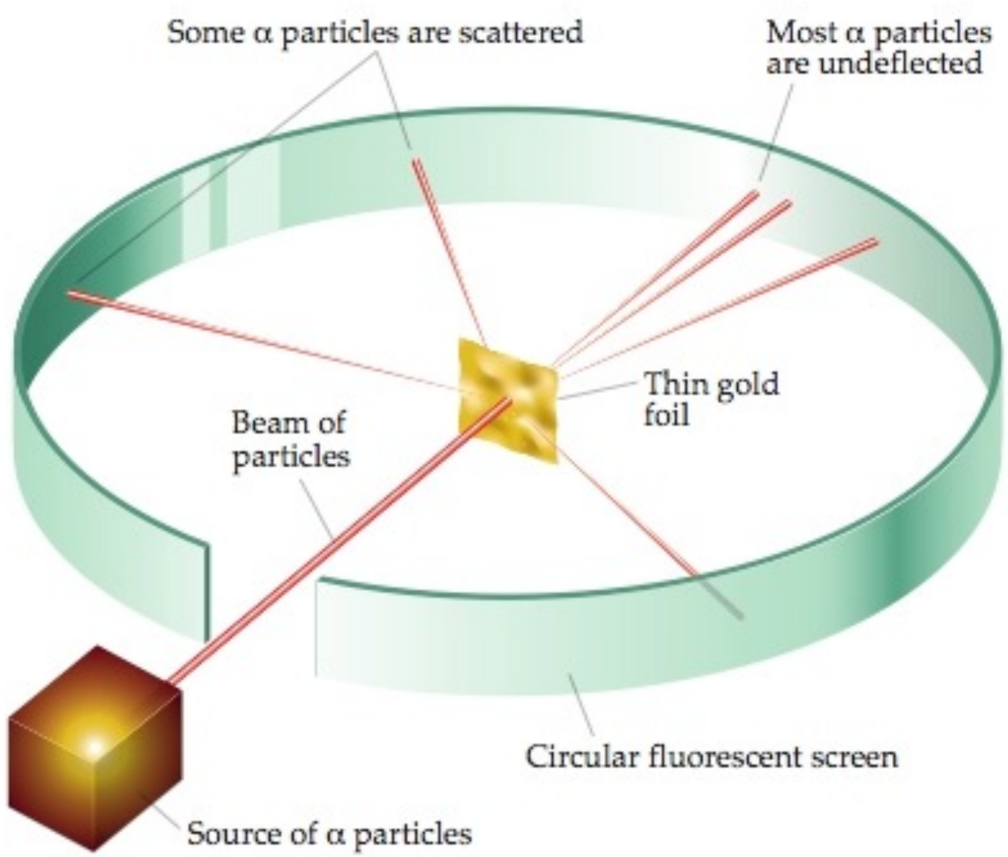


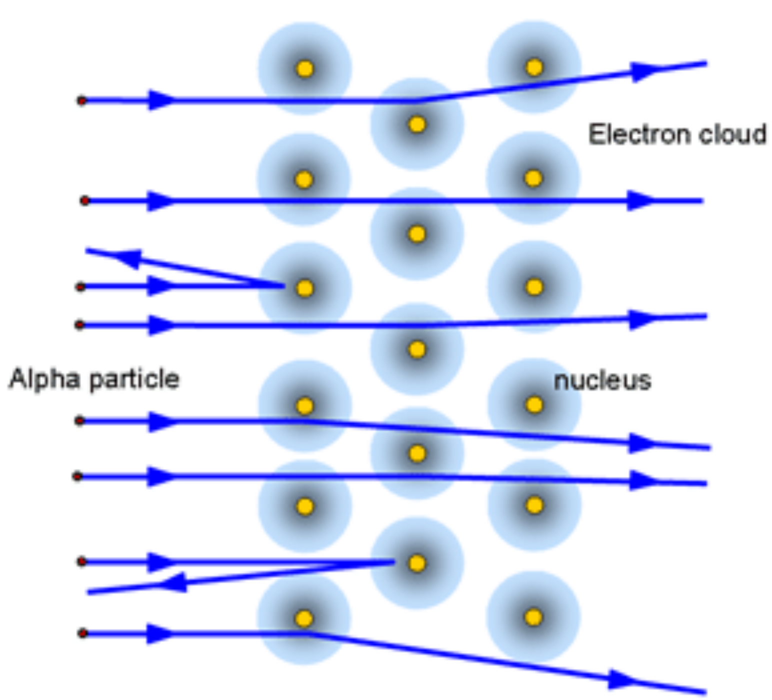


- **Yield of hard probes is expected to scale with N_{coll} in absence of medium effect**

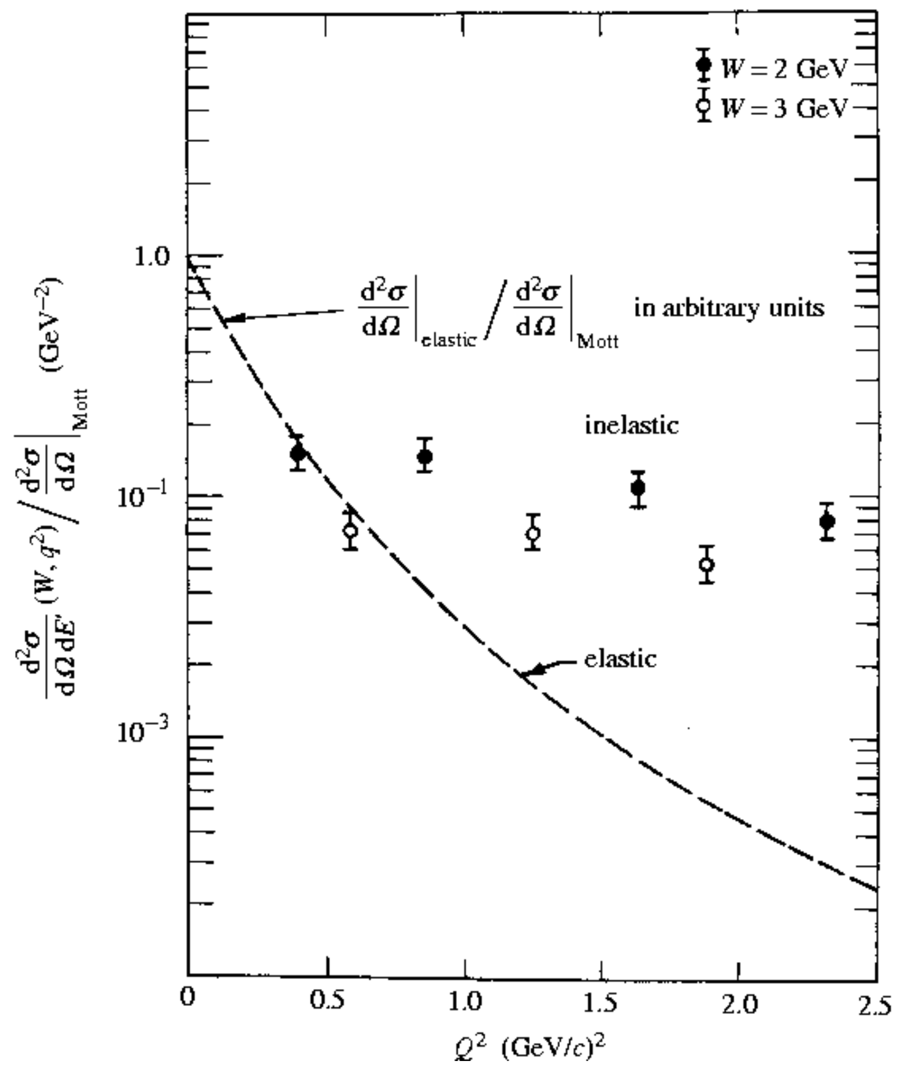
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{\text{coll}} \cdot dN_{pp}/dp_T} \begin{cases} > 1 & \text{enhancement} \\ = 1 & \text{no medium effect} \\ < 1 & \text{suppression} \end{cases}$$

How to Probe the Structure of Matter?

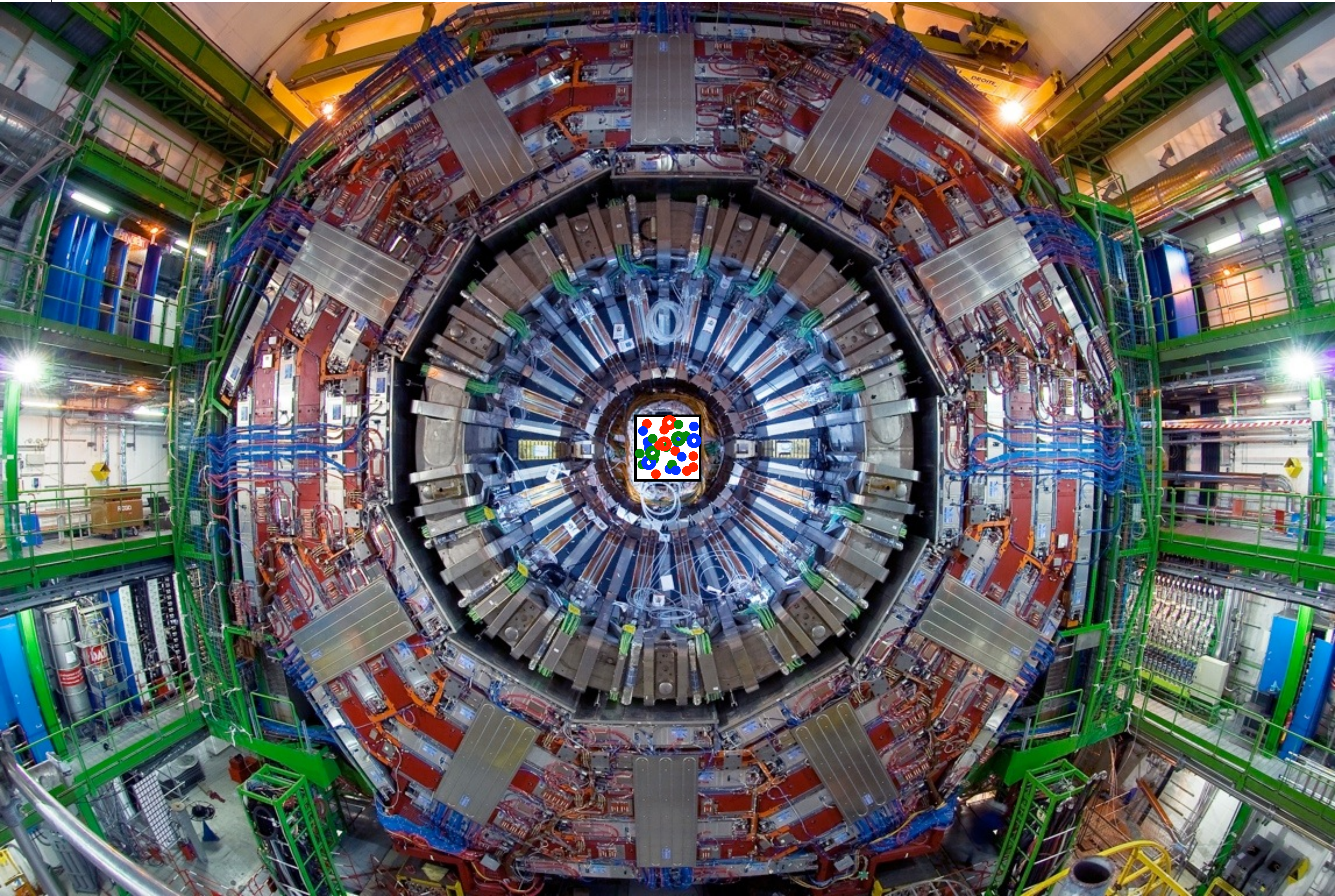




- Rutherford experiment:
  - α → atom: discovery of the nucleus
  - elastic collisions
- SLAC electron scattering:
  - e → proton: discovery of quarks
  - inelastic collisions



Rutherford Experiment on a QGP?



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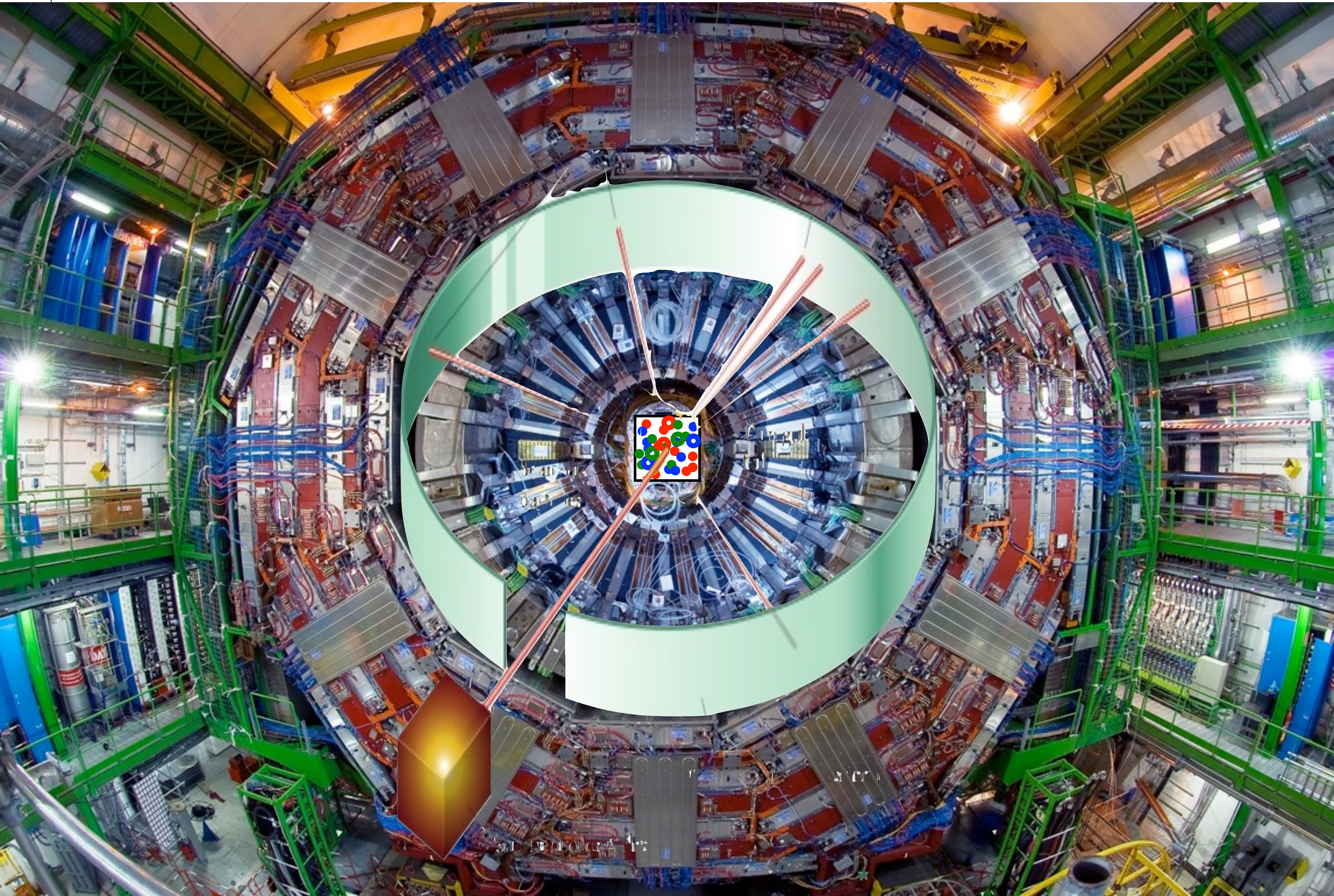
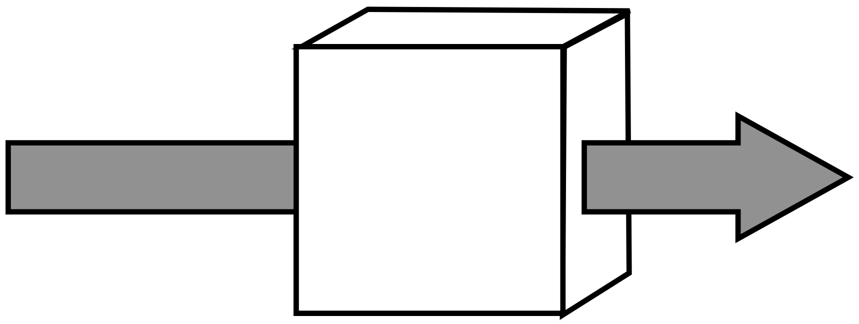


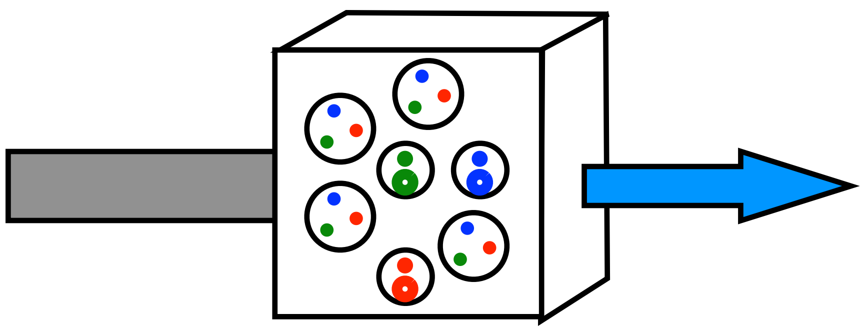
How to Probe the QGP?

vacuum



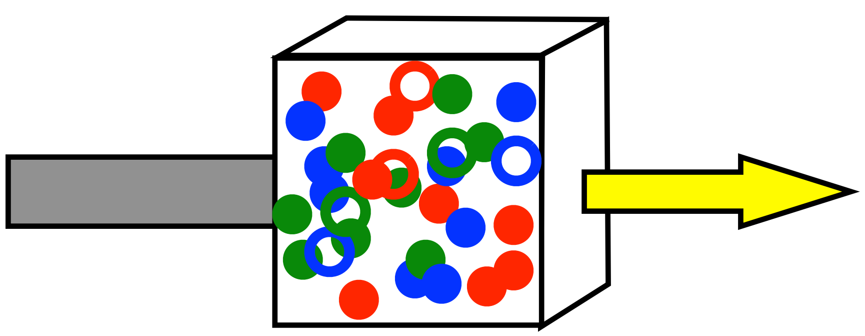
- Has to be well understood in pp collisions
  - hard probes calculable in pQCD

hadronic matter



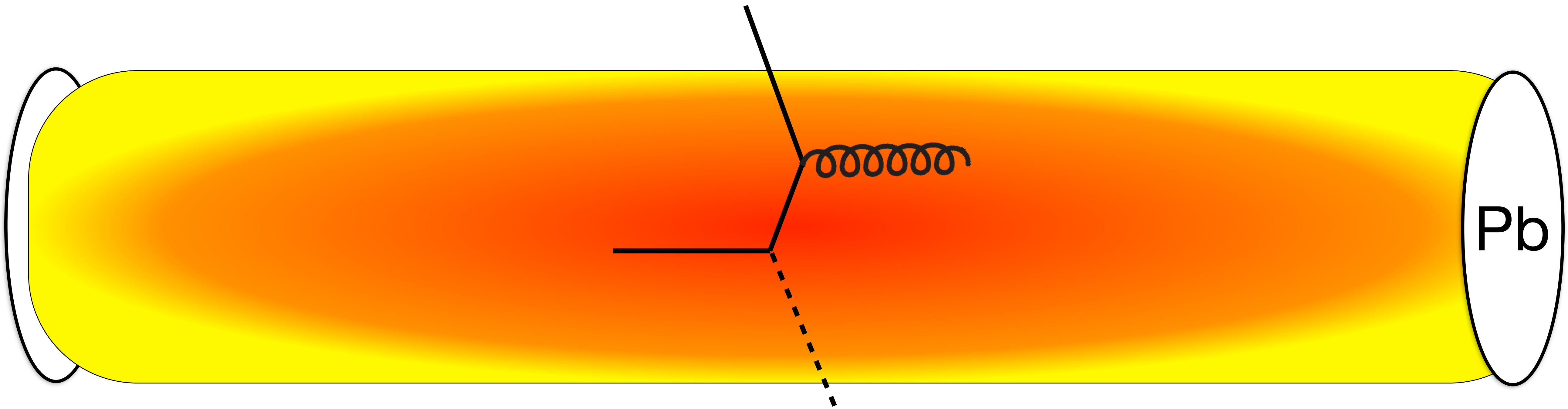
- Effect of hadronic matter has to be understood and accounted for
  - measure in p-A collisions

QGP



- Has to be strongly affected by the QGP

Hard Probes of the QGP



- Create the probes as part of the collision
- Create probes before the QGP forms
- Control probes not affected by the QGP to calibrate measurements
- Collisions without QGP to test cold nuclear matter effects
    - pp collisions, p-nucleus collisions, light-ion collisions

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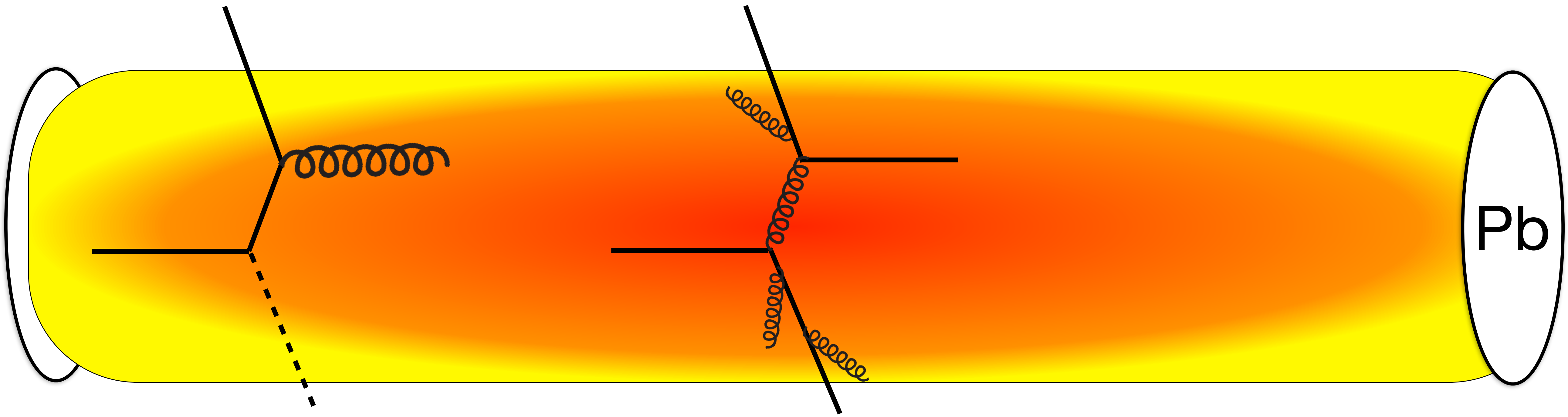

control probes **density ⇔ energy loss**

(γ, W±, Z) **(hadrons, jets, open heavy flavour)**

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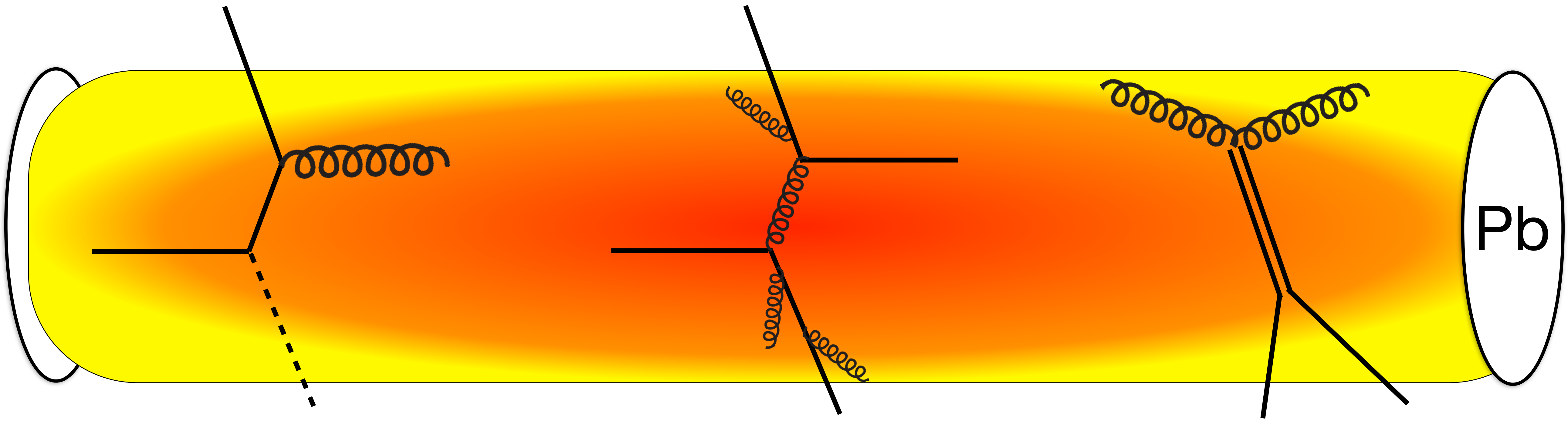

control probes **density ⇔ energy loss** **temperature ⇔ dissociation**

(γ, W$^{\pm}$, Z) **(hadrons, jets, open heavy flavour)** **(quarkonia)**

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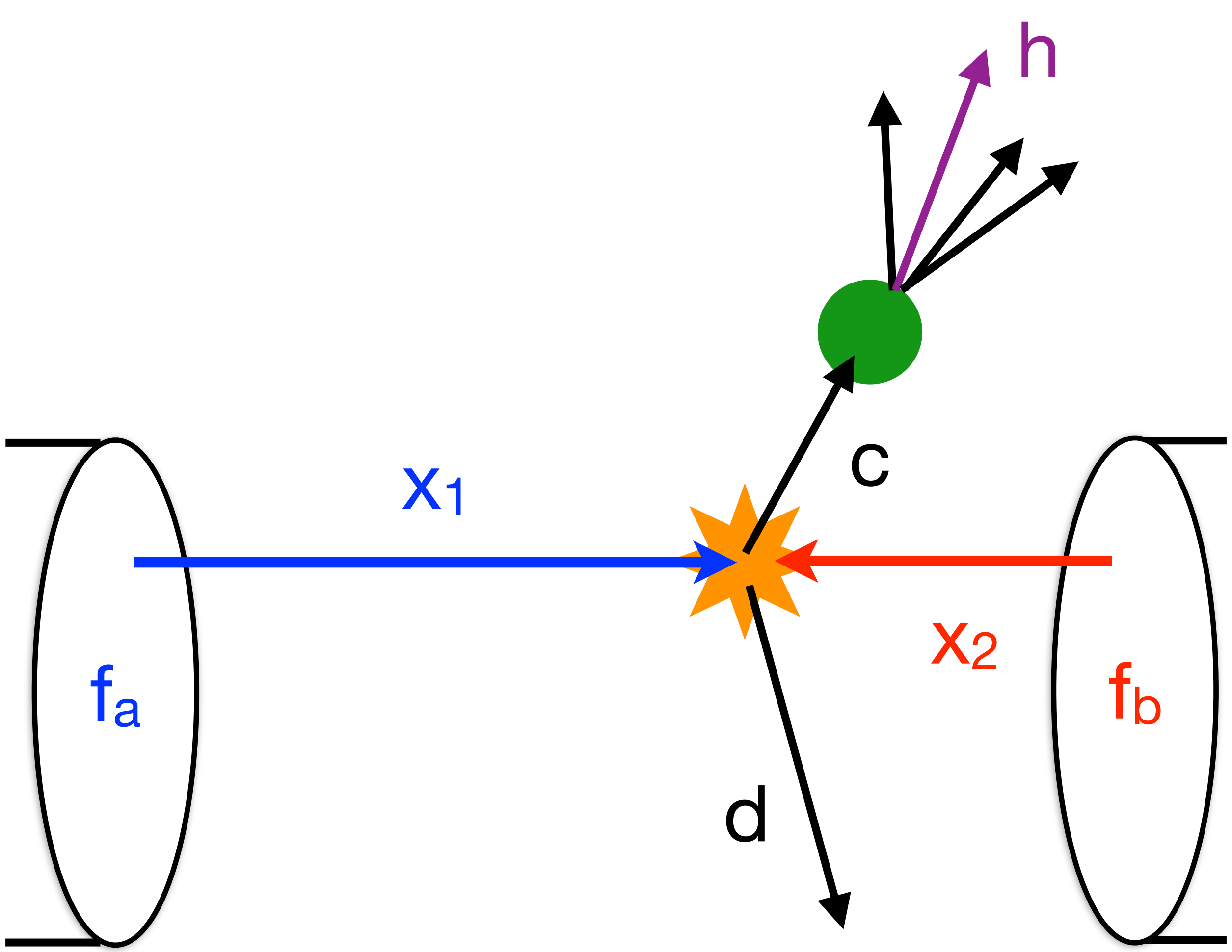
Production of Hard Probes

- **QCD Factorization Theorem: cross section factorizes in**
  - **probability to find parton with momentum fraction x (non-perturbative)**
  - **scattering cross section given partons with momenta x_1 and x_2 (perturbative)**
  - **fragmentation function of outgoing partons (non-perturbative)**

$$z_c = \frac{p_T^h}{p_T^c}$$

Q^2: “resolution power”
x: “inelasticity”

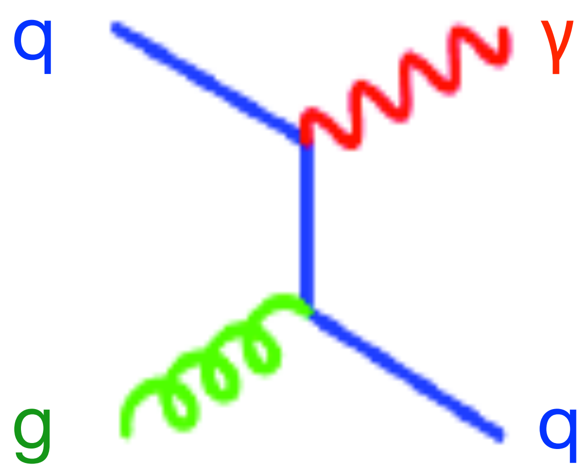


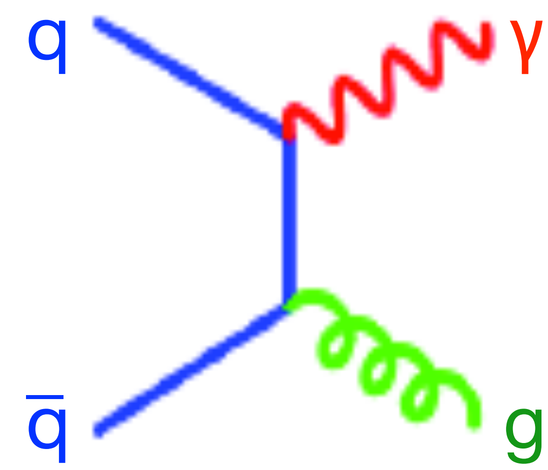
$$\sigma_h = \sum_{a,b,c} \int_0^1 dx_1\, dx_2\, f_a(x_1, Q^2) \times f_b(x_2, Q^2) \times \hat{\sigma}_{ab\to c}(x_1, x_2, Q^2) \times D_{c\to h}(z_c, Q^2)$$

Electroweak Bosons

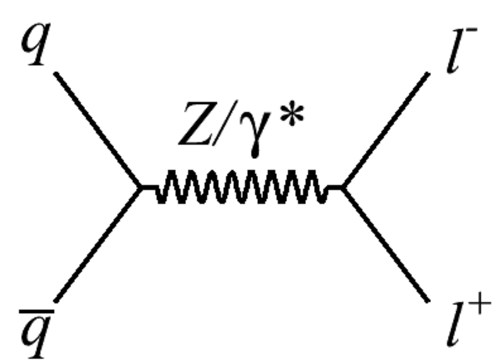
Electroweak Particle Production at LO

- Direct photons
  - Quark-gluon Compton scattering or quark-antiquark annihilation

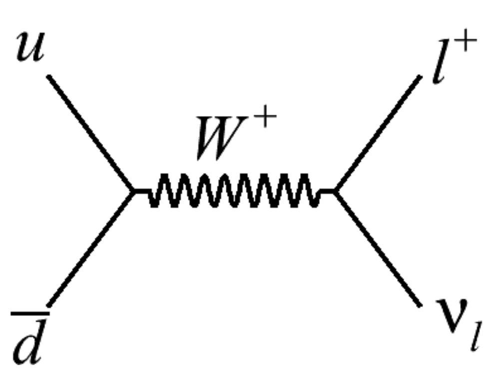


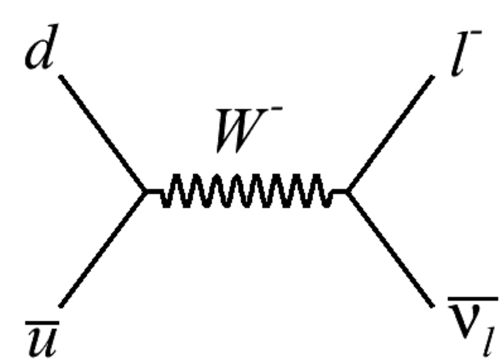


- Z boson
  - quark-antiquark annihilation

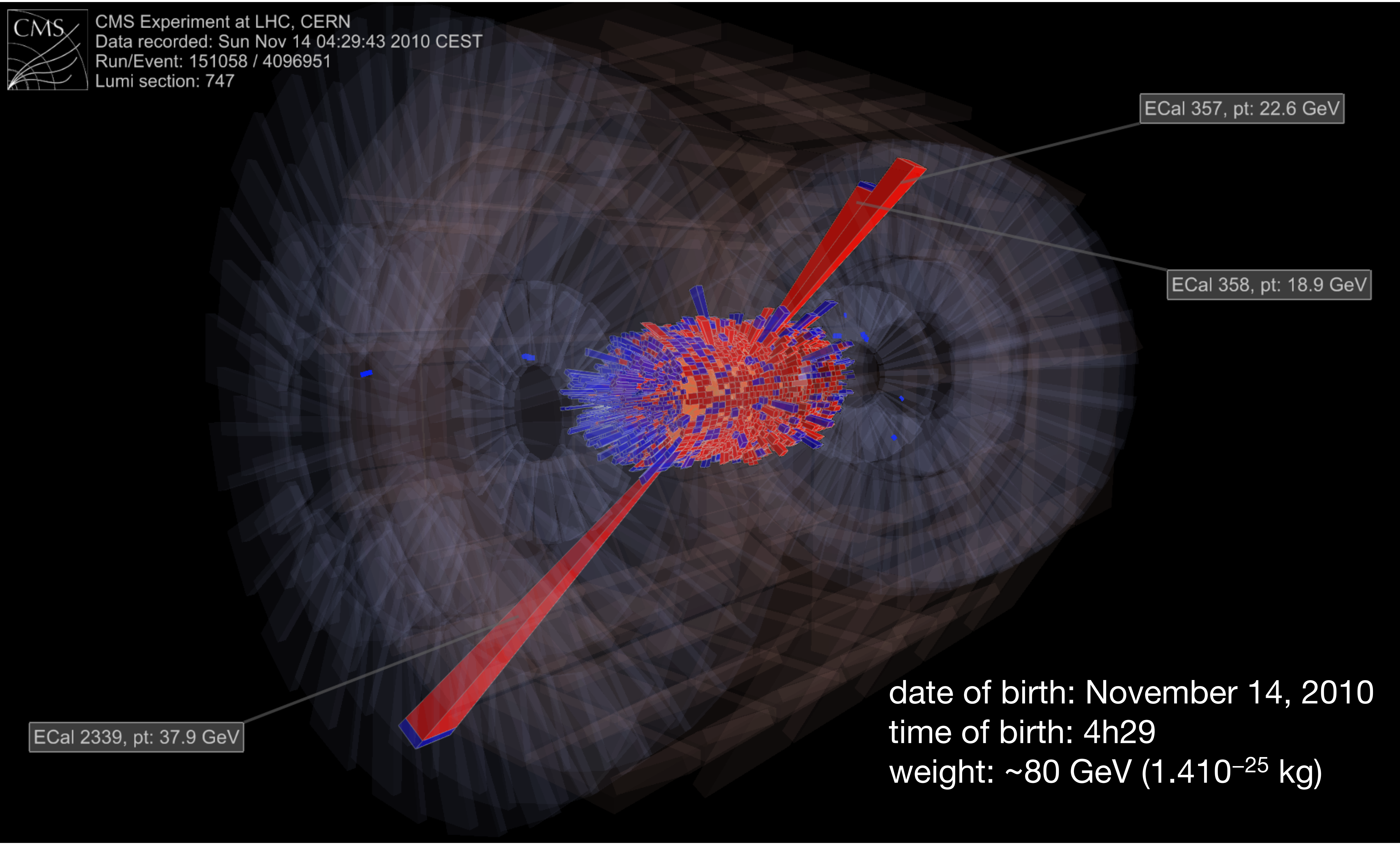


- W± boson
  - quark-antiquark annihilation with different flavours



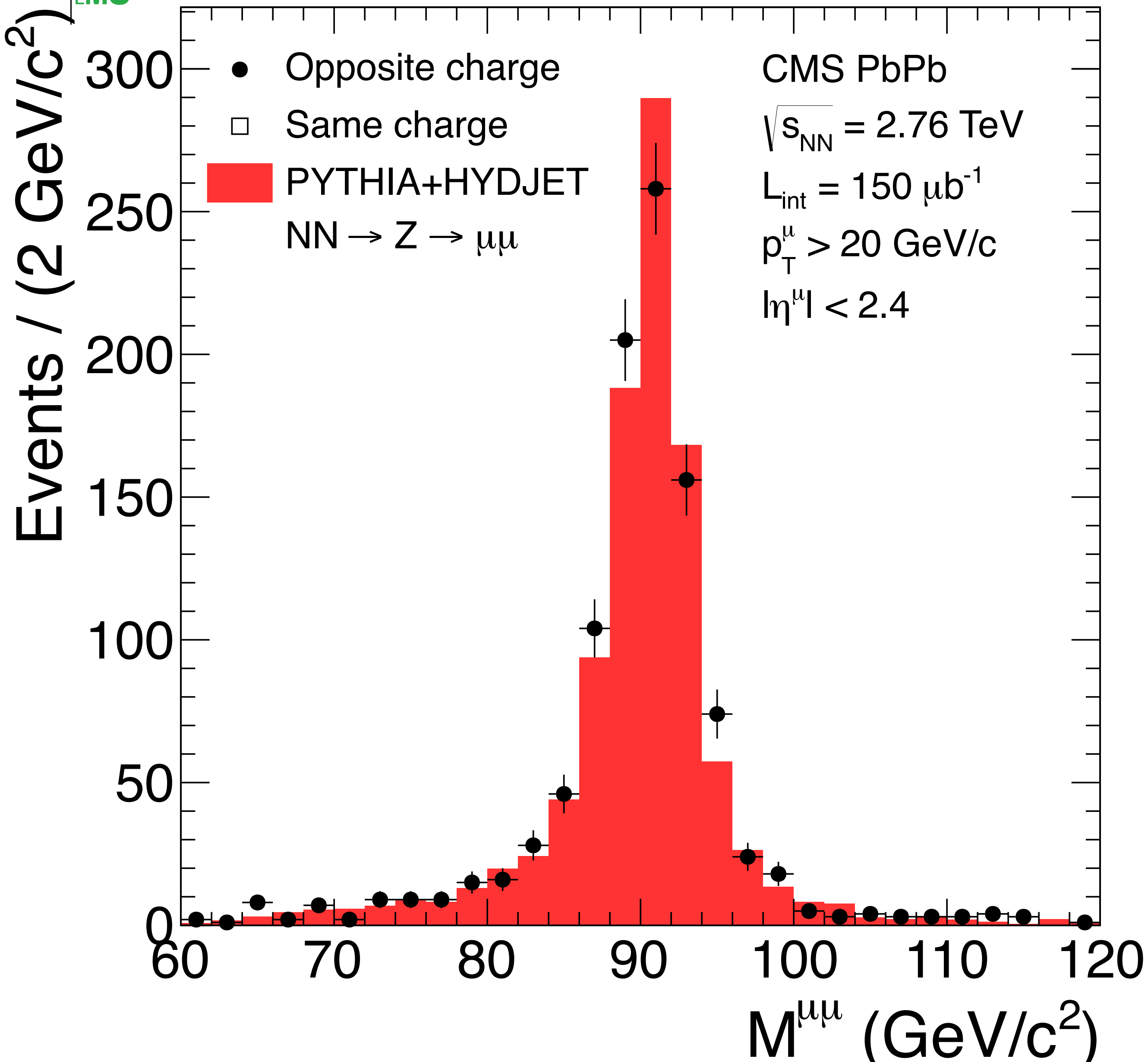


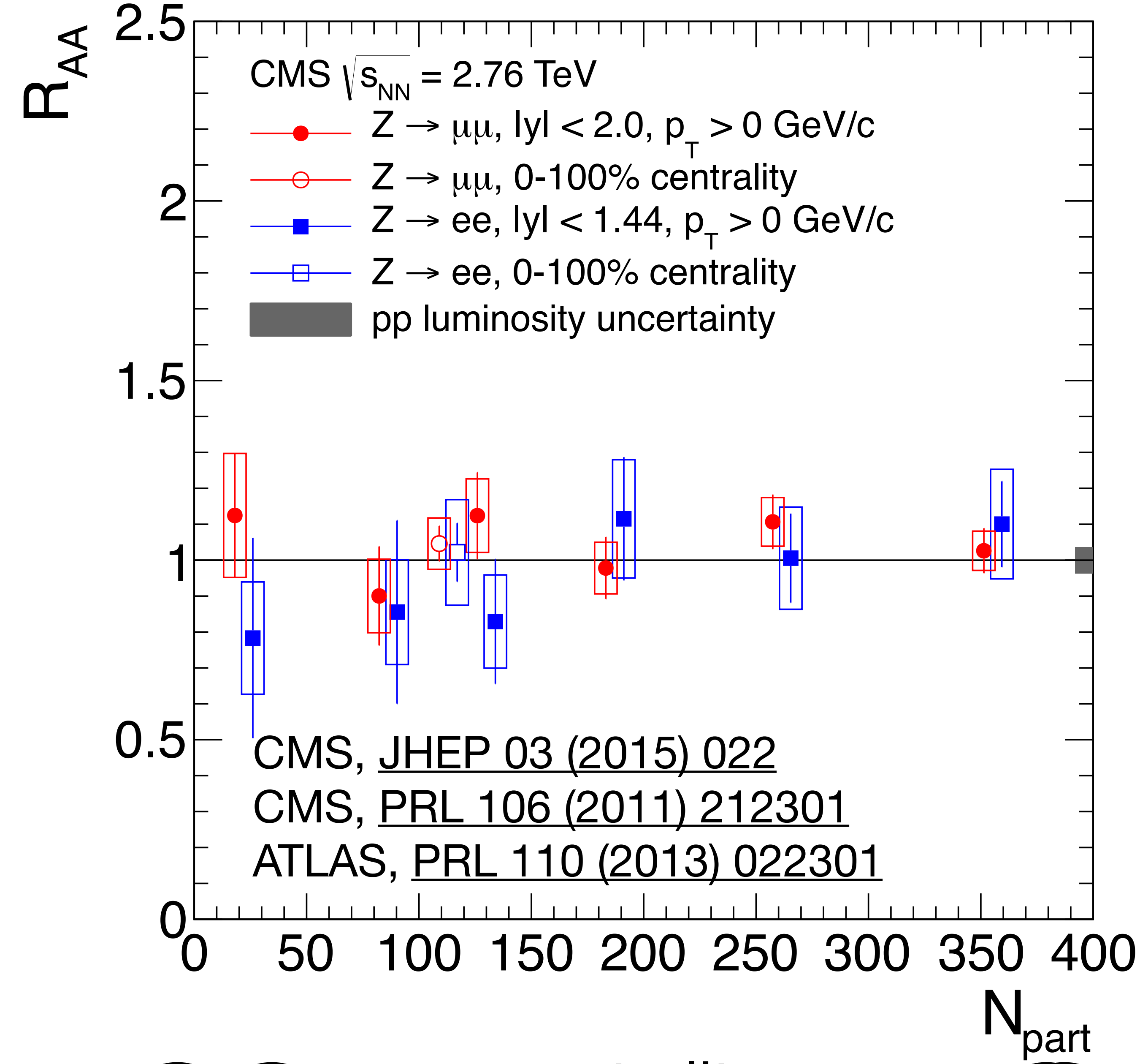
First Z boson ever in Heavy Ions



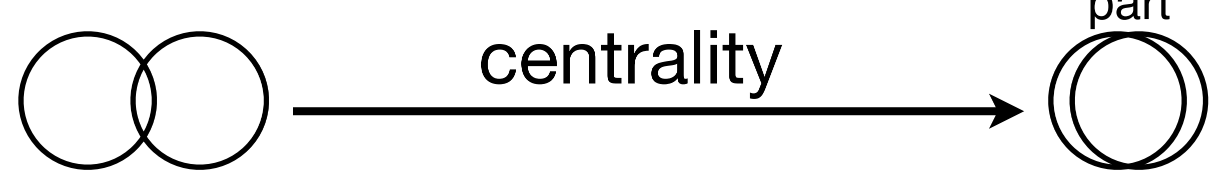
date of birth: November 14, 2010
time of birth: 4h29
weight: ~80 GeV (1.410^{-25} kg)

Z bosons in Pb–Pb at 2.76 TeV





$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{\rm coll} \cdot dN_{pp}/dp_T} \begin{cases} > 1 & \text{enhancement} \\ = 1 & \text{no medium effect} \\ < 1 & \text{suppression} \end{cases}$$



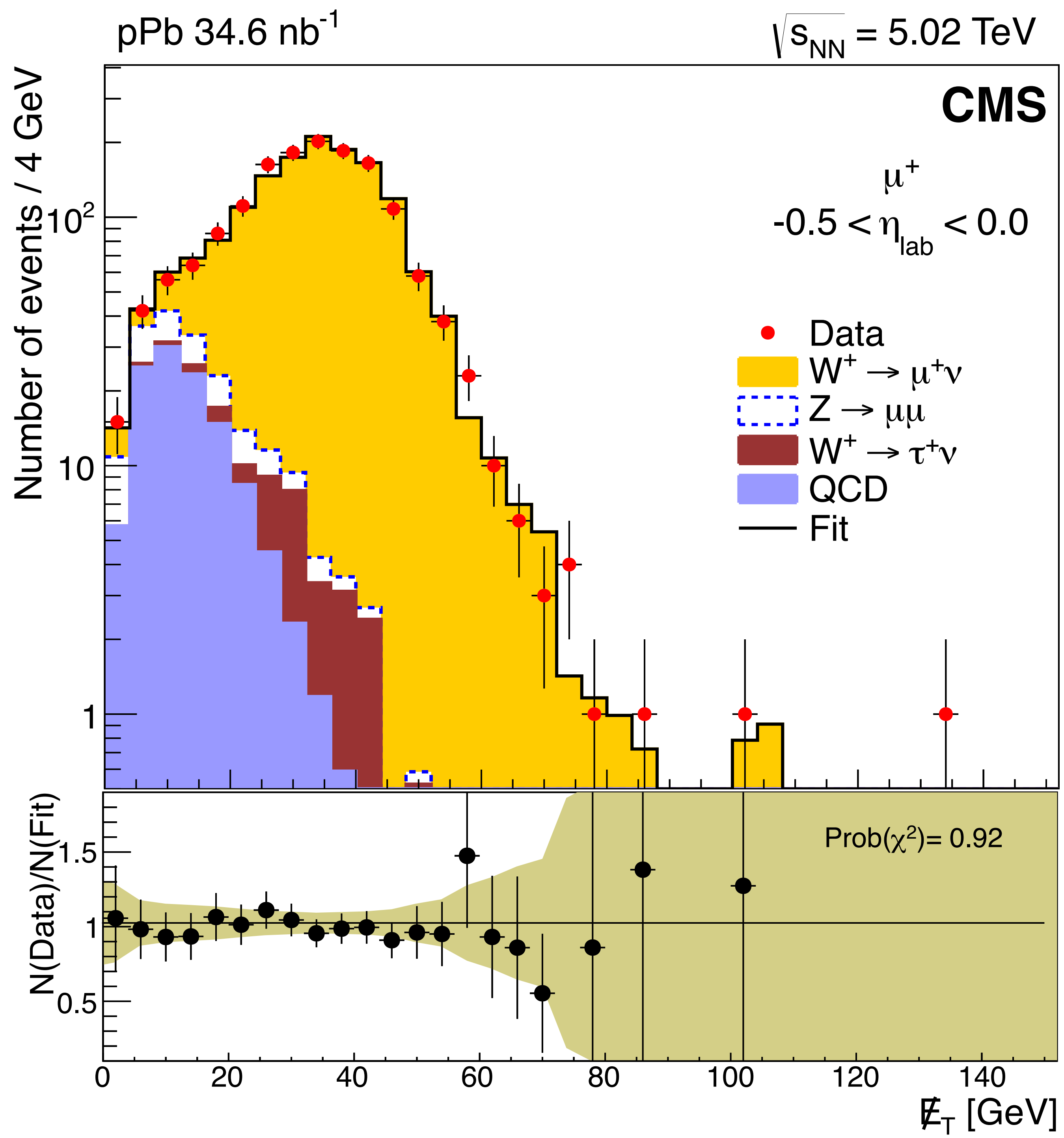
- Pb–Pb data and Pythia (pp) agree in invariant mass spectrum
- **R_{AA} = 1: Yield scales with number of binary collisions**

W bosons in pPb at 5.02 TeV

- W → $\mu\ \nu_\mu$
  - neutrino escapes undetected
  - Harder to detect, but 10× more than Z
- Energy conservation: $\Sigma\ E_T = 0$
  - neutrino = missing E_T
  - $\Sigma E_z \neq 0$ (because $x_1 \neq x_2$)
- Missing E_T background
  - Z with only one reconstructed μ
  - W → τ
  - Multi-jet events (QCD) with a jet outside acceptance
- Calculate m_T using missing E_T

$$m_T = \sqrt{p_T^\mu \not{E}_T (1 - \cos\phi)}$$

CMS, PLB 750 (2015) 565



W bosons in pPb at 5.02 TeV

- W → μ ν_μ
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  - Harder to detect, but 10× more than Z
- Energy conservation: Σ E_T = 0
  - neutrino = missing E_T
  - ΣE_z ≠ 0 (because x_1 ≠ x_2)
- Missing E_T background
  - Z with only one reconstructed μ
  - W → τ
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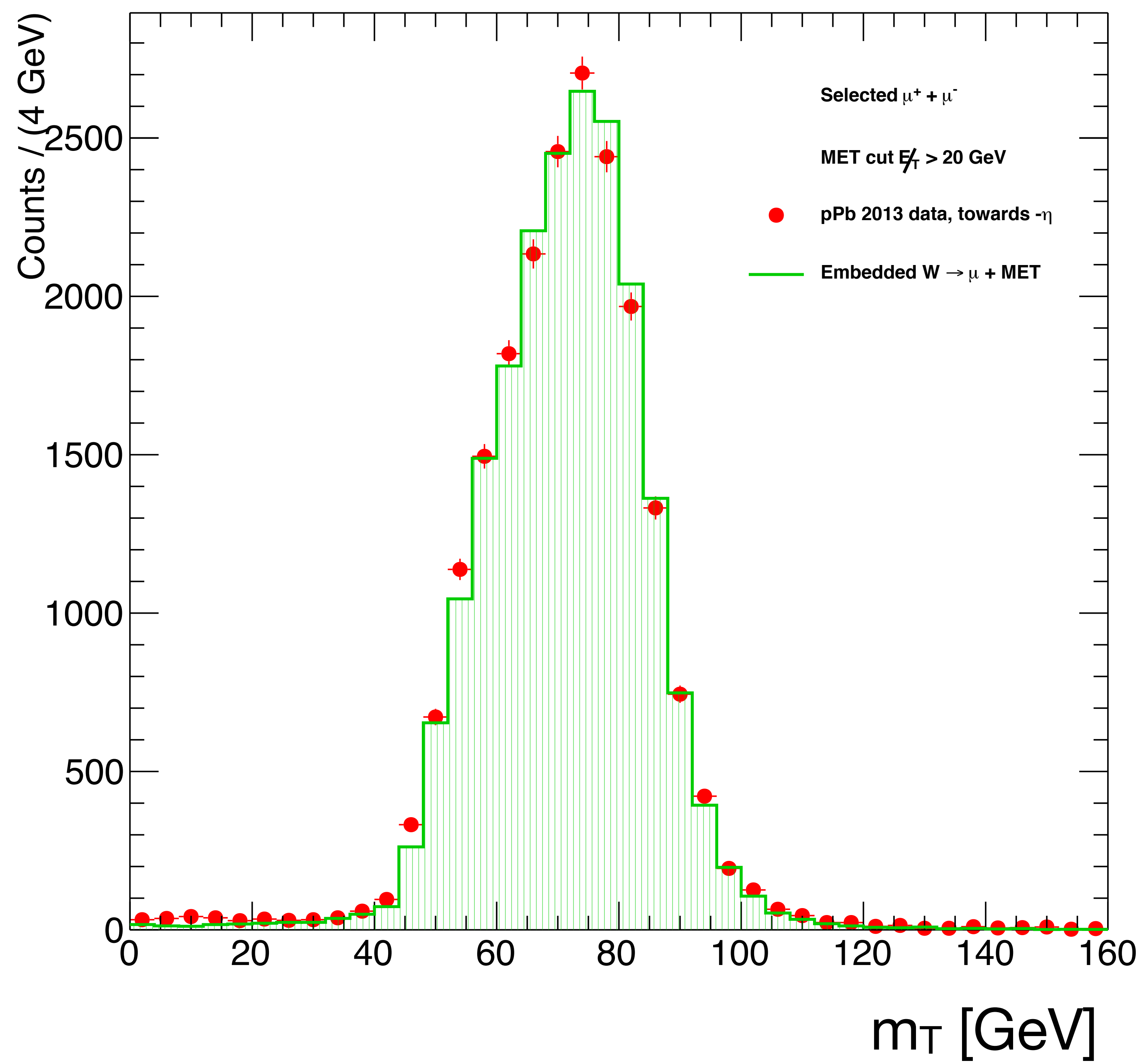
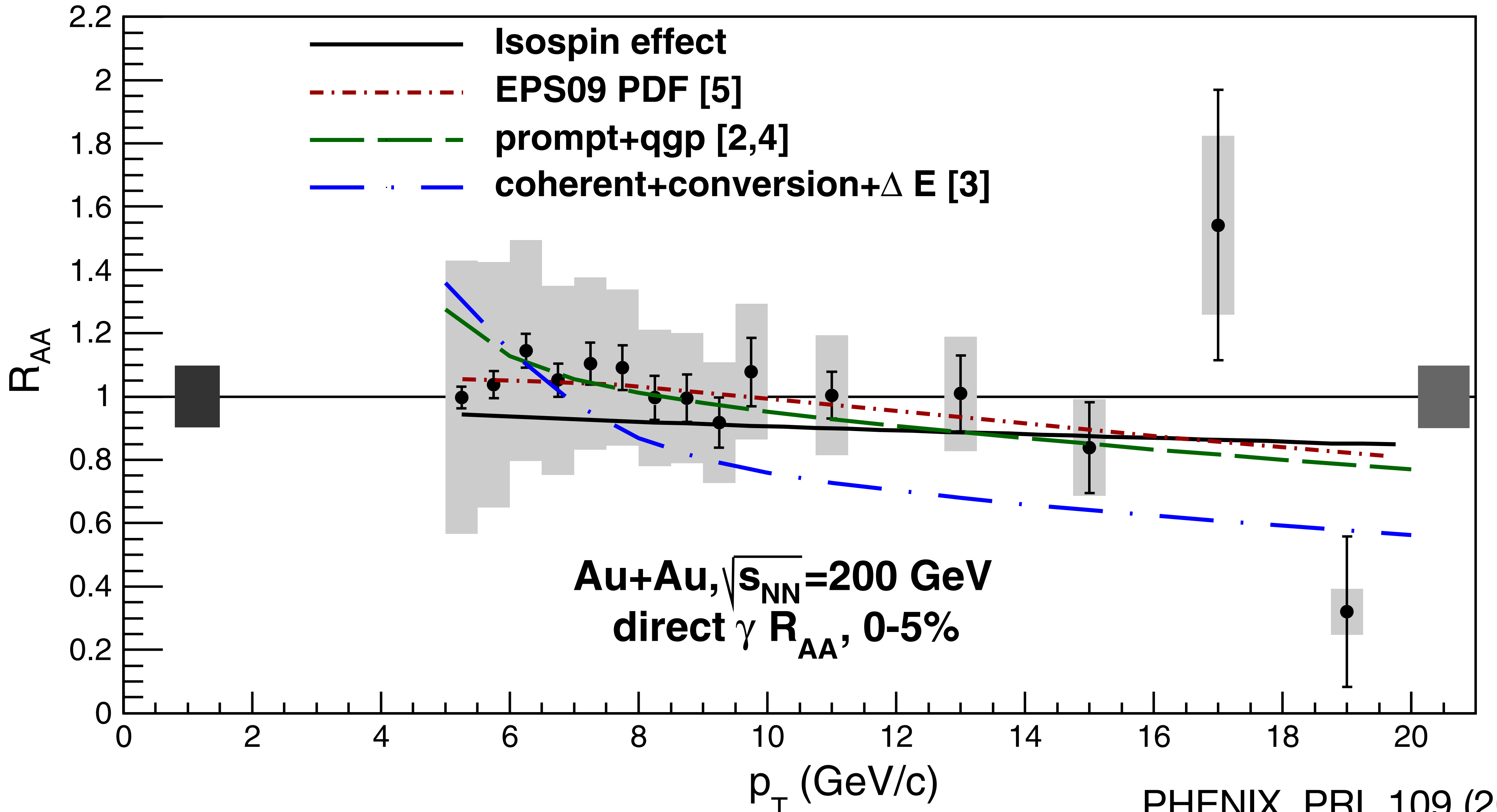
CMS, PLB 750 (2015) 565



Direct Photons at RHIC

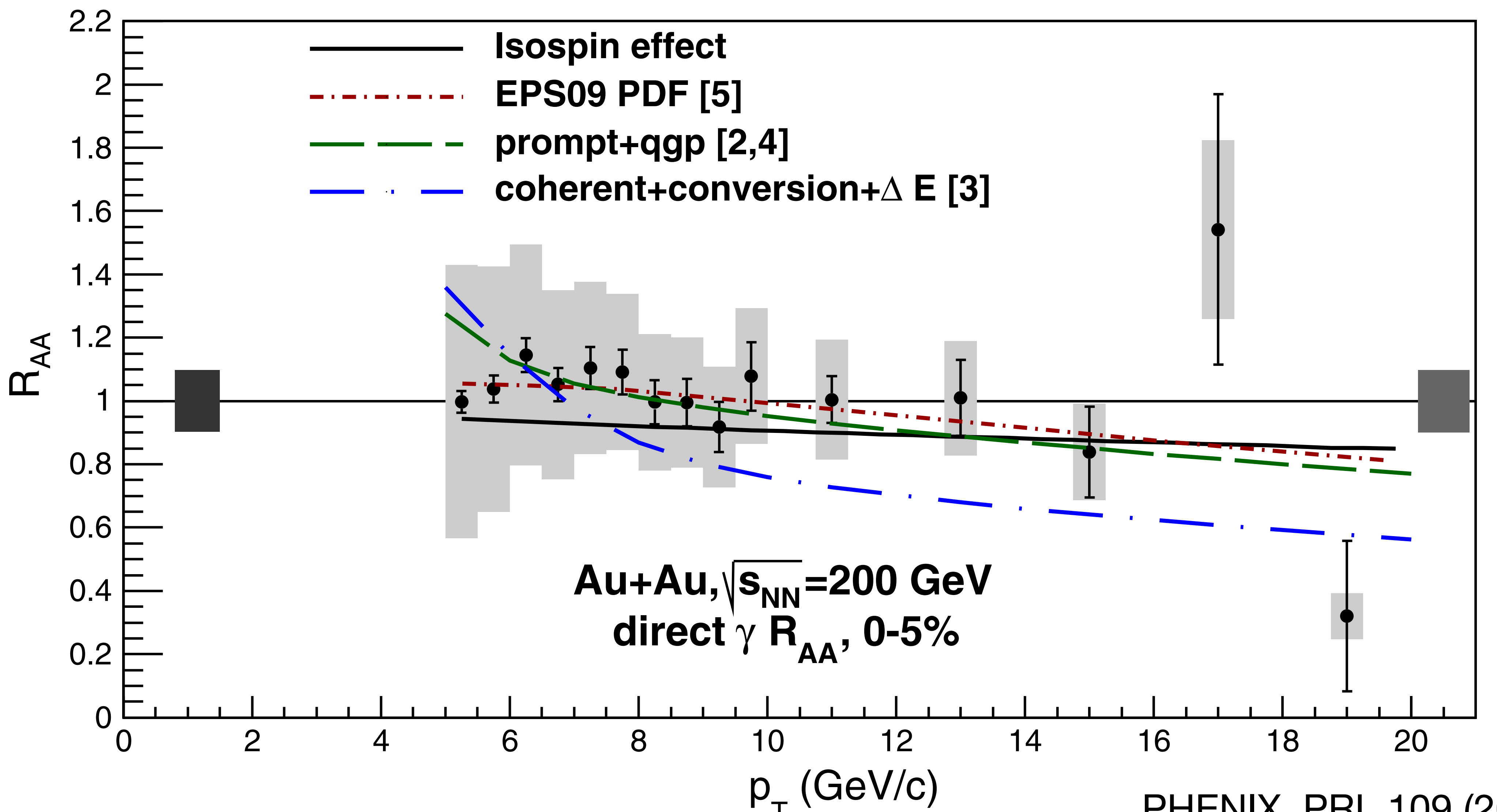


PHENIX, PRL 109 (2012) 152302

- No strong nuclear modifications down to p_T = 5 GeV/c
  - systematic uncertainties limit measurement at low p_T

Direct Photons at RHIC

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{\text{coll}} \cdot dN_{pp}/dp_T} \begin{cases} > 1 & \text{enhancement} \\ = 1 & \text{no medium effect} \\ < 1 & \text{suppression} \end{cases}$$



PHENIX, PRL 109 (2012) 152302

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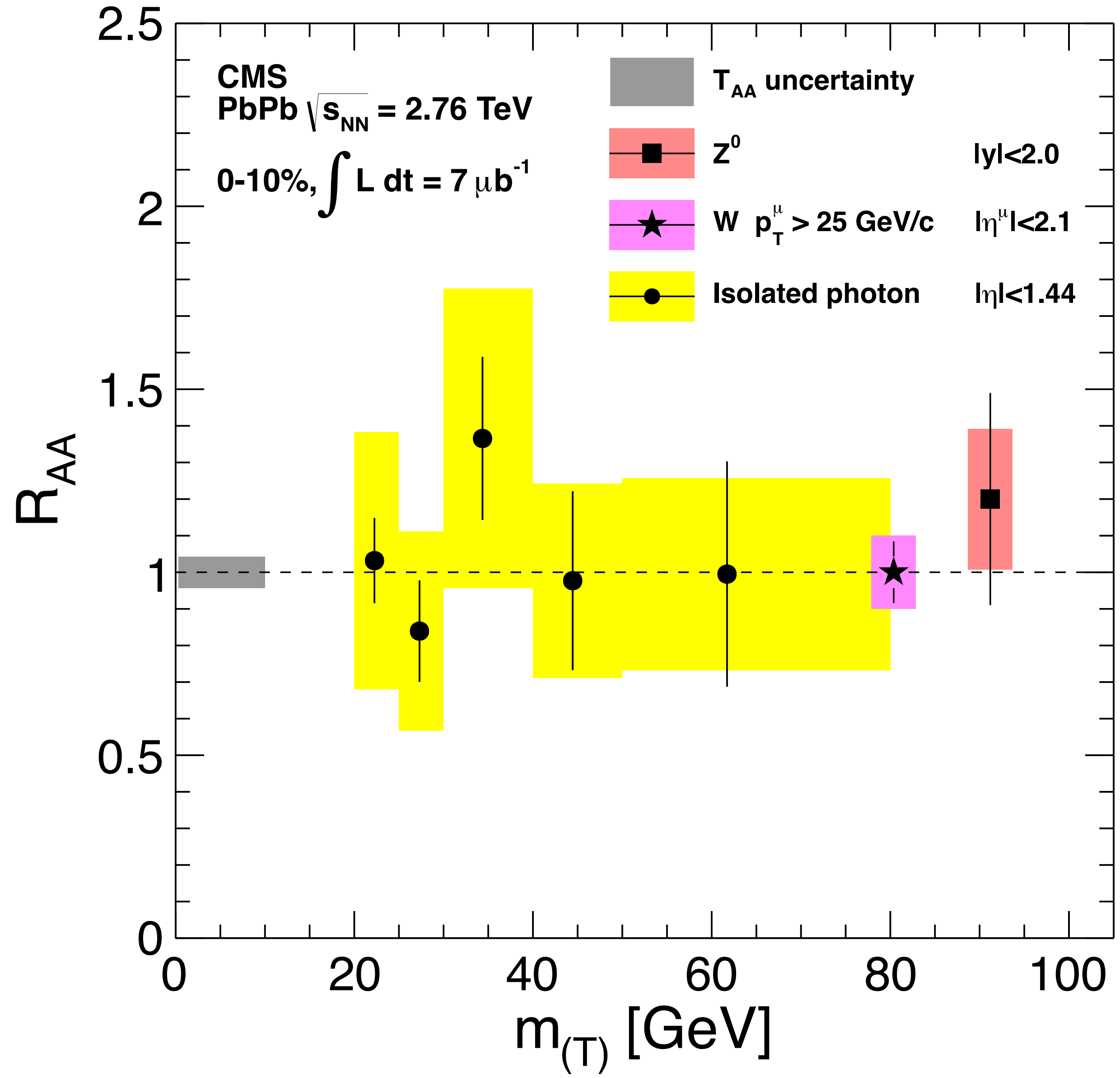
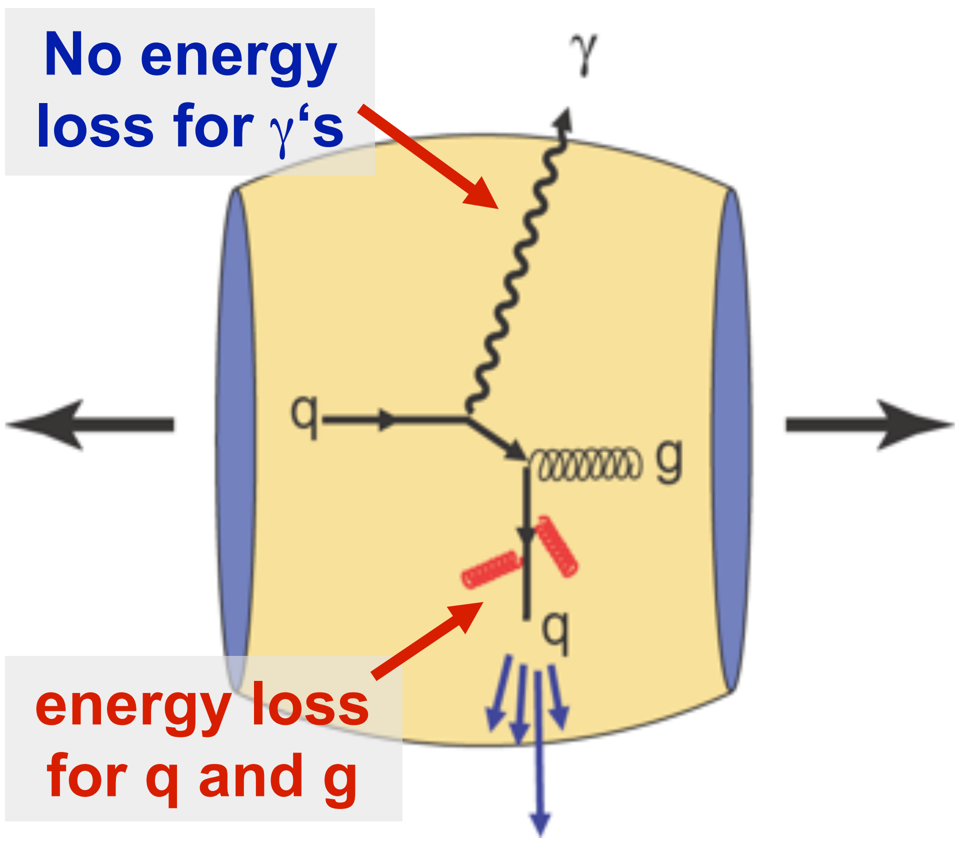
Summary: EWK Probes



- **Yield of electroweak bosons scales with the N_{coll}**
  - confirmation of Glauber model
  - validates concept of R_{AA} to measure modifications of hard probes
- W and Z bosons new probes at the LHC
- Nuclear PDF effects at the level of 10–15%

Jets

Jet Quenching



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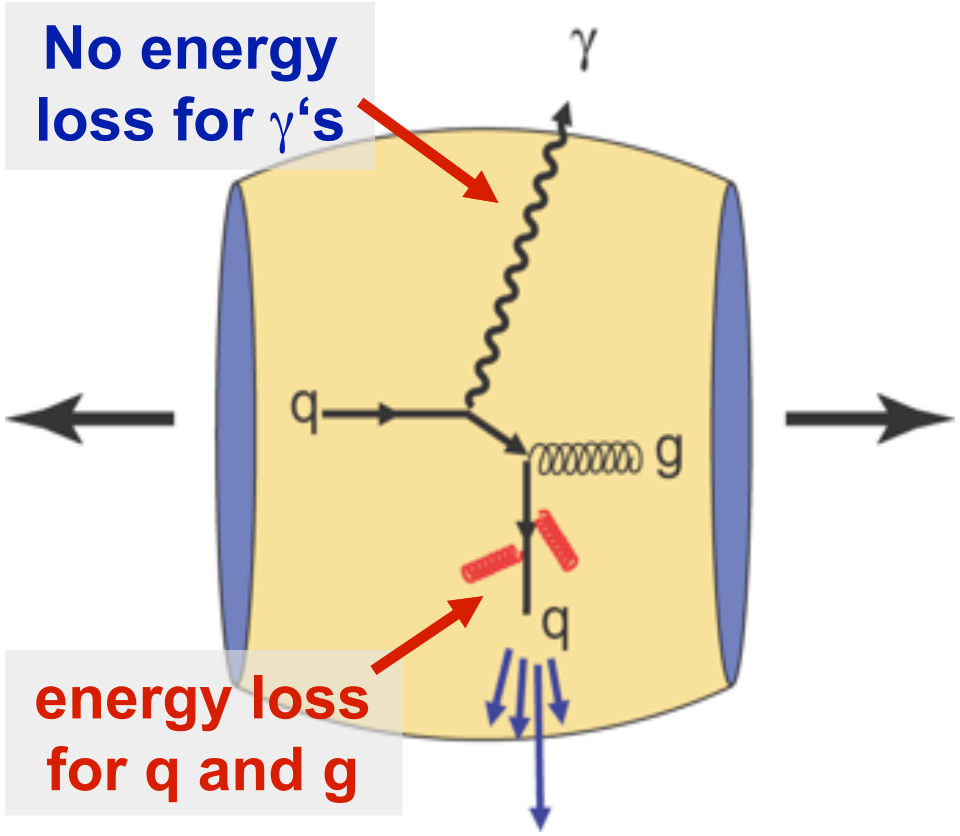

- Naive scaling of hard probes with number of inelastic NN collisions
  - Pb–Pb = many independent pp collisions

Jet Quenching

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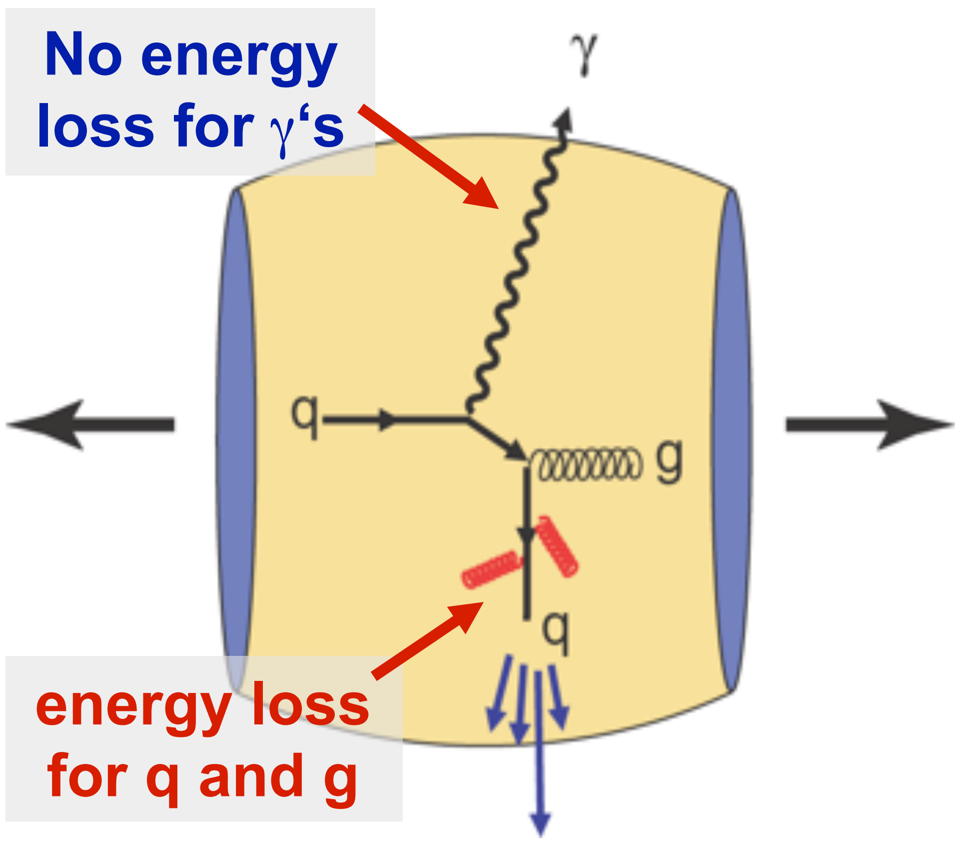

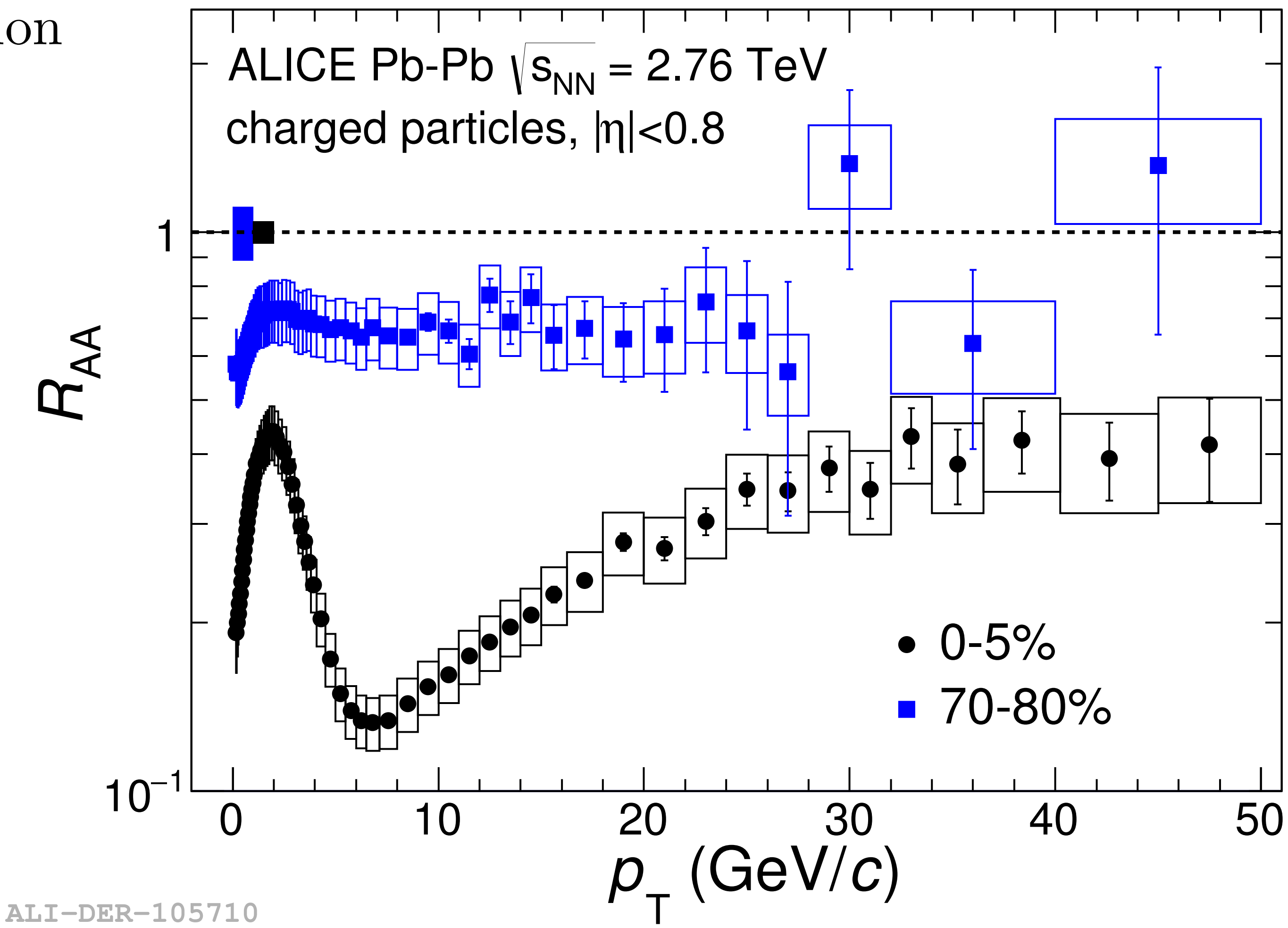

- Naive scaling of hard probes with number of inelastic NN collisions
  - Pb–Pb = many independent pp collisions
- **Strong suppression of high-p_T hadrons in central Pb–Pb**
  - energy loss in the QGP

Jet Quenching

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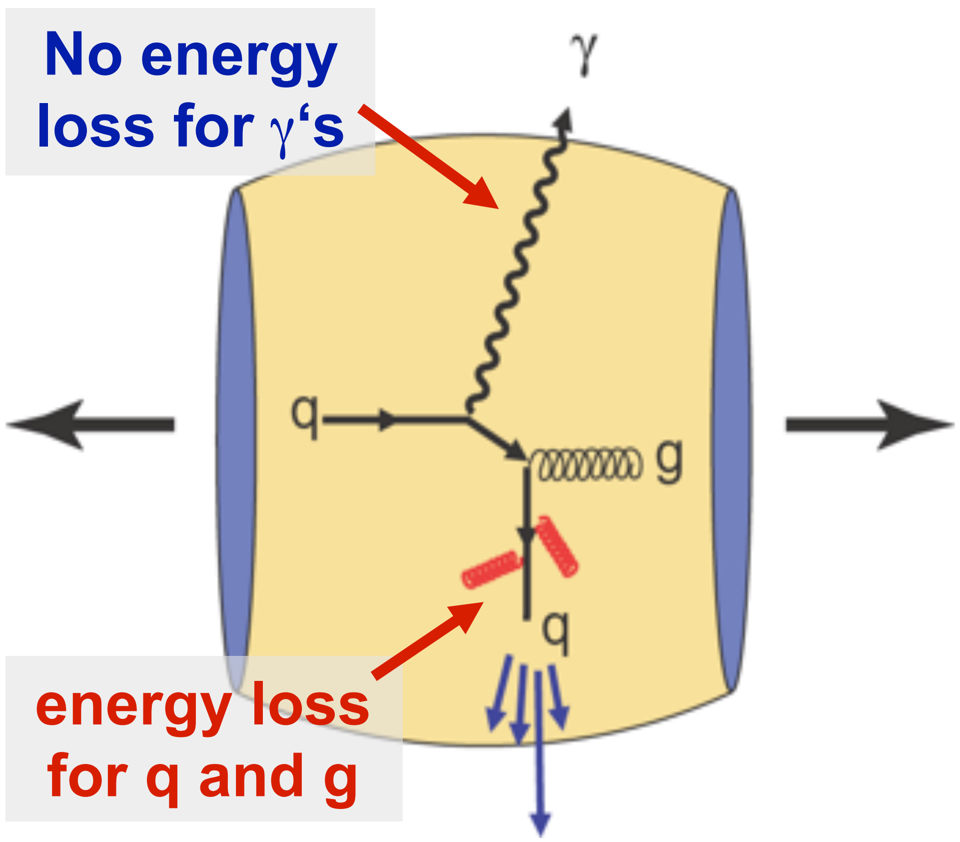
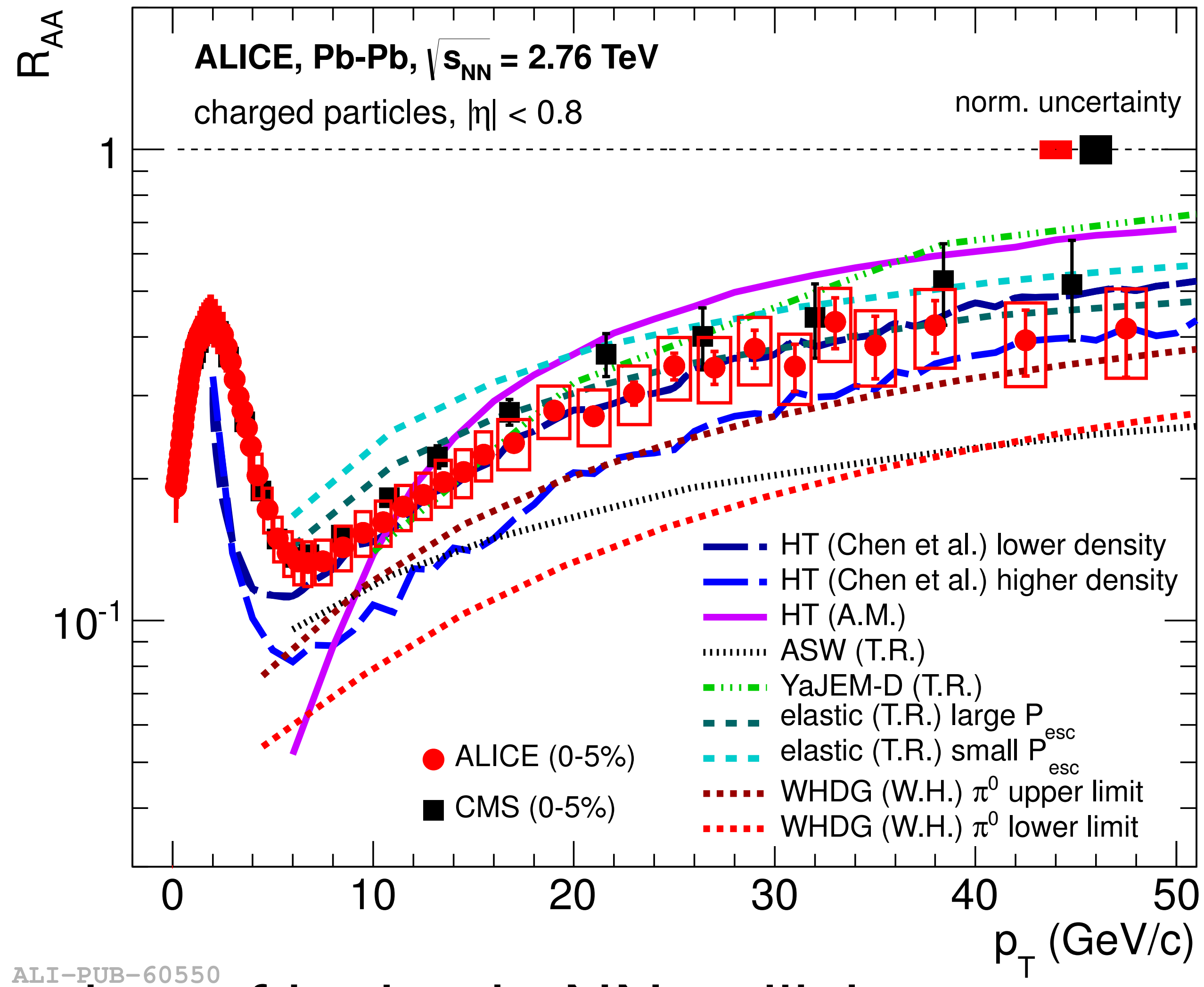
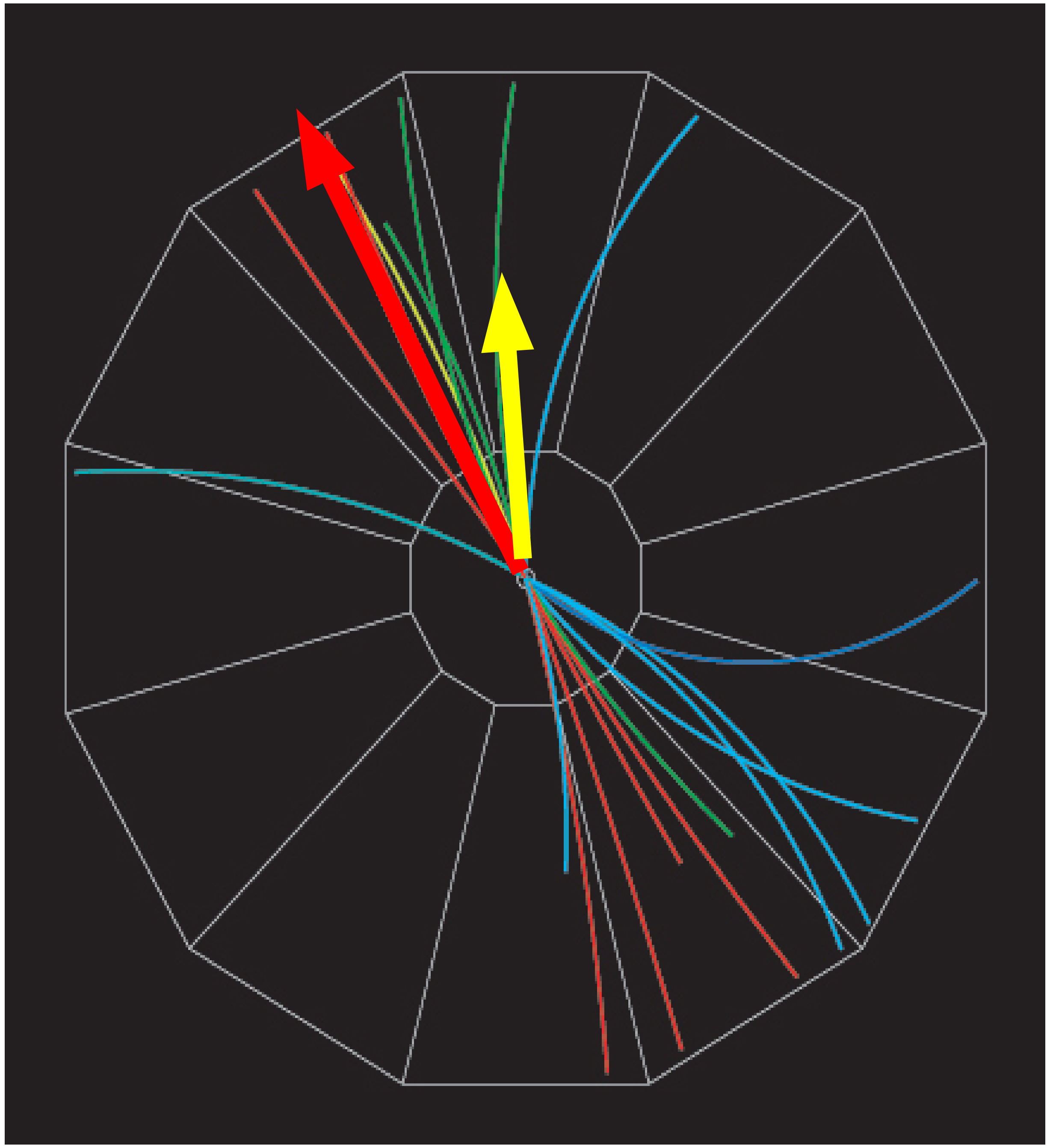
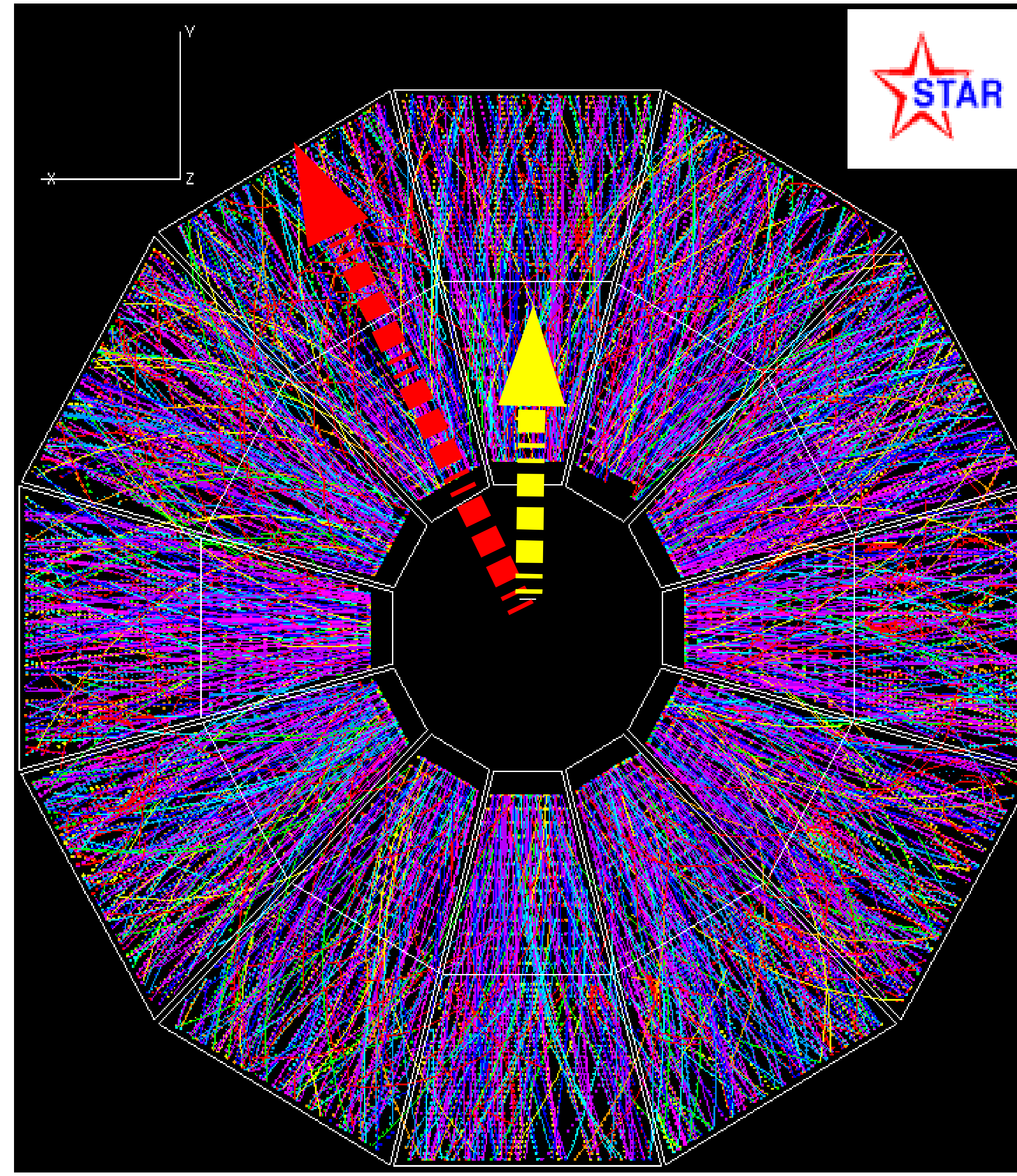




- Naive scaling of hard probes with number of inelastic NN collisions
  - Pb–Pb = many independent pp collisions
- **Strong suppression of high-p_T hadrons in central Pb–Pb**
  - energy loss in the QGP
- Model QGP energy loss: fundamental properties of the strong interaction

Dihadron Correlations

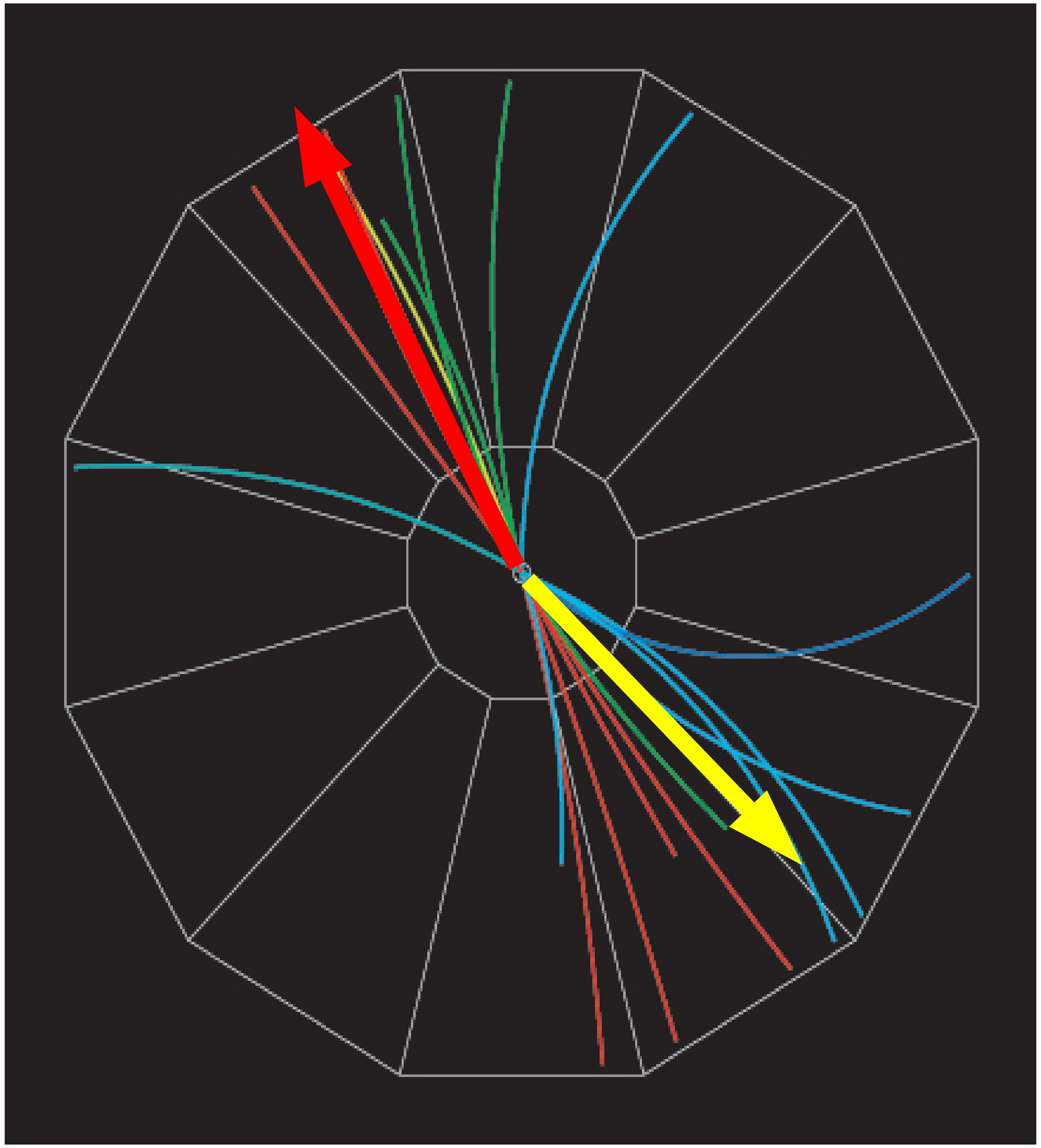




pp → jet+jet
($\sqrt{s}$ = 200 GeV)

Au–Au → X
($\sqrt{s_{NN}}$ = 200 GeV)

Dihadron Correlations



pp → jet+jet
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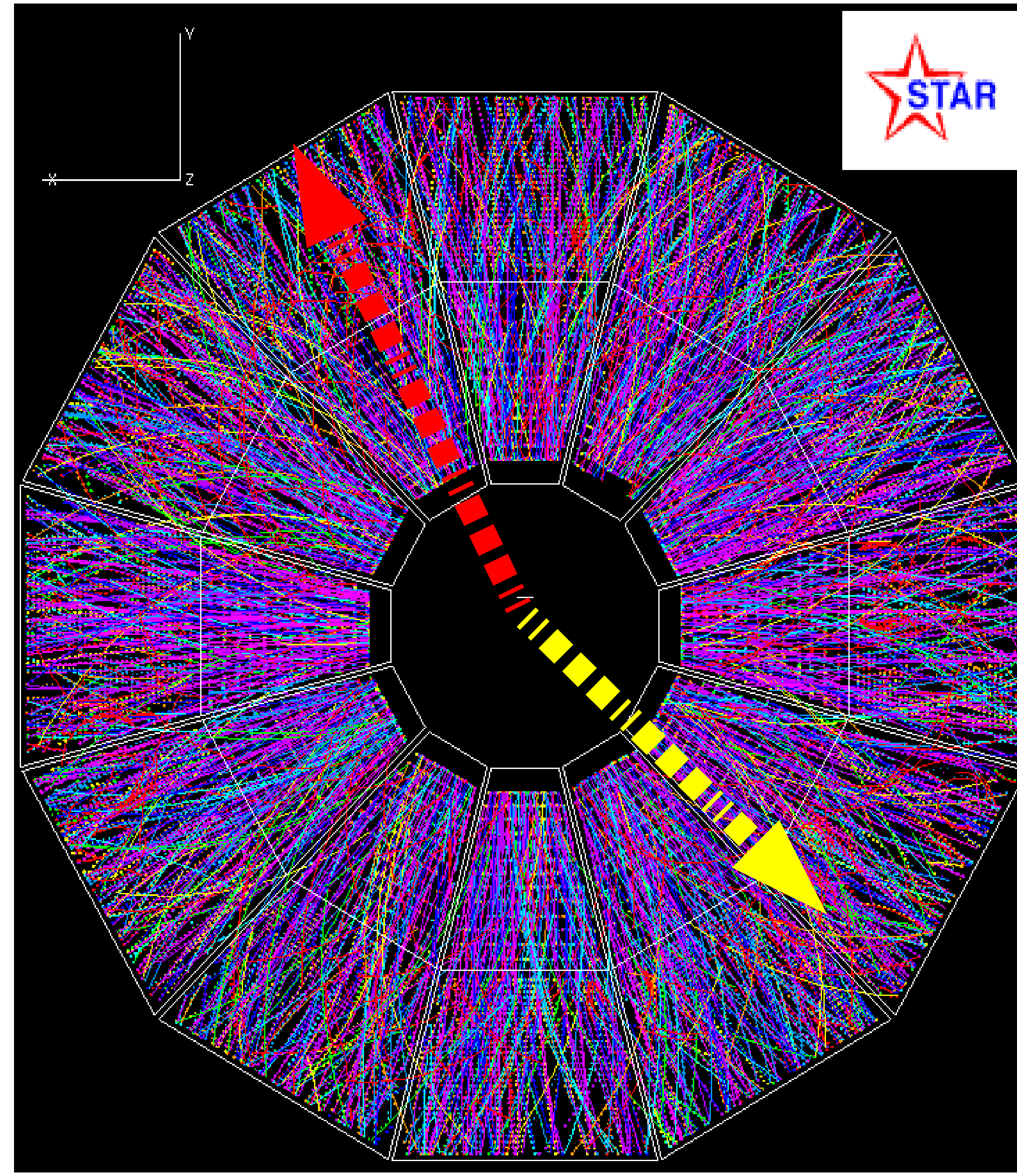
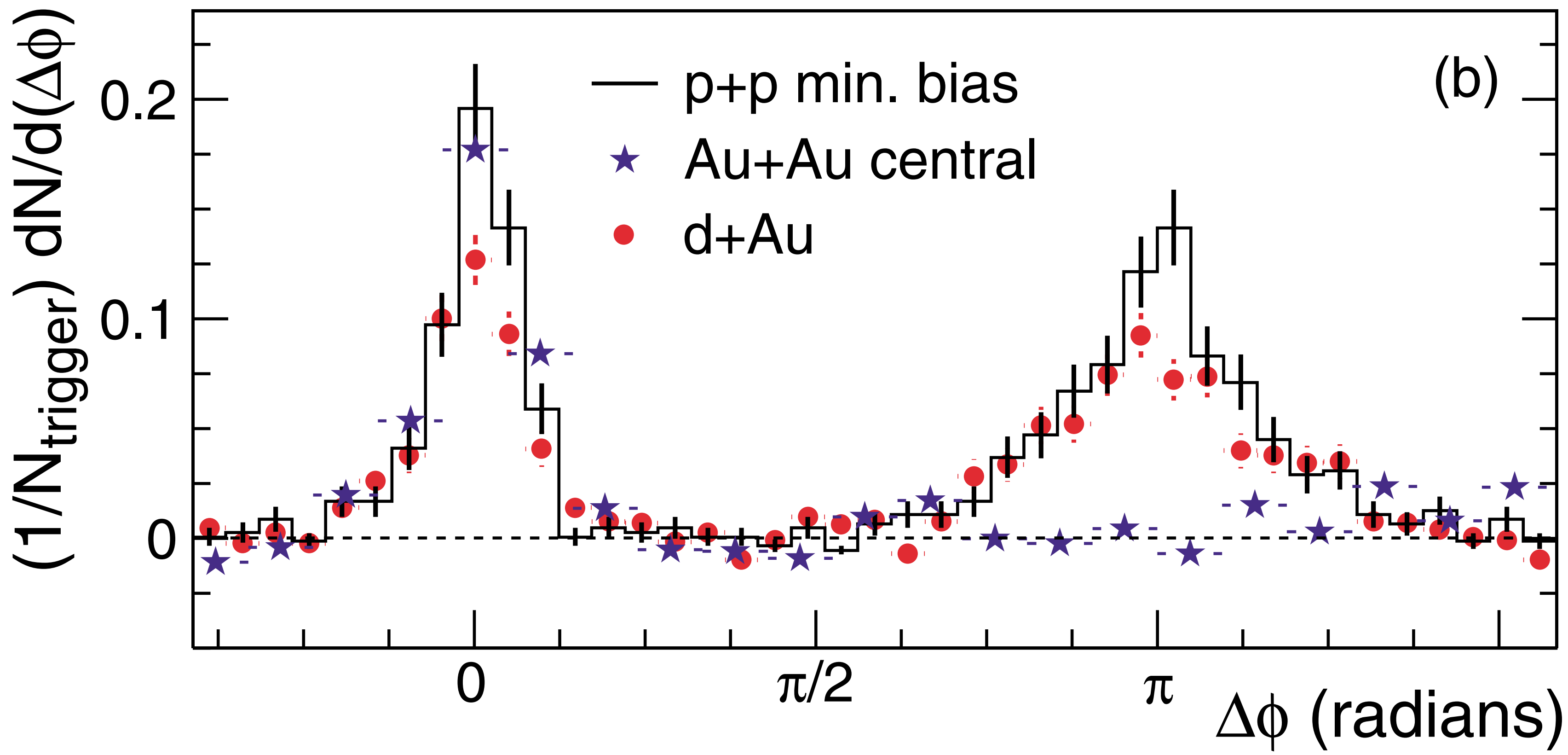


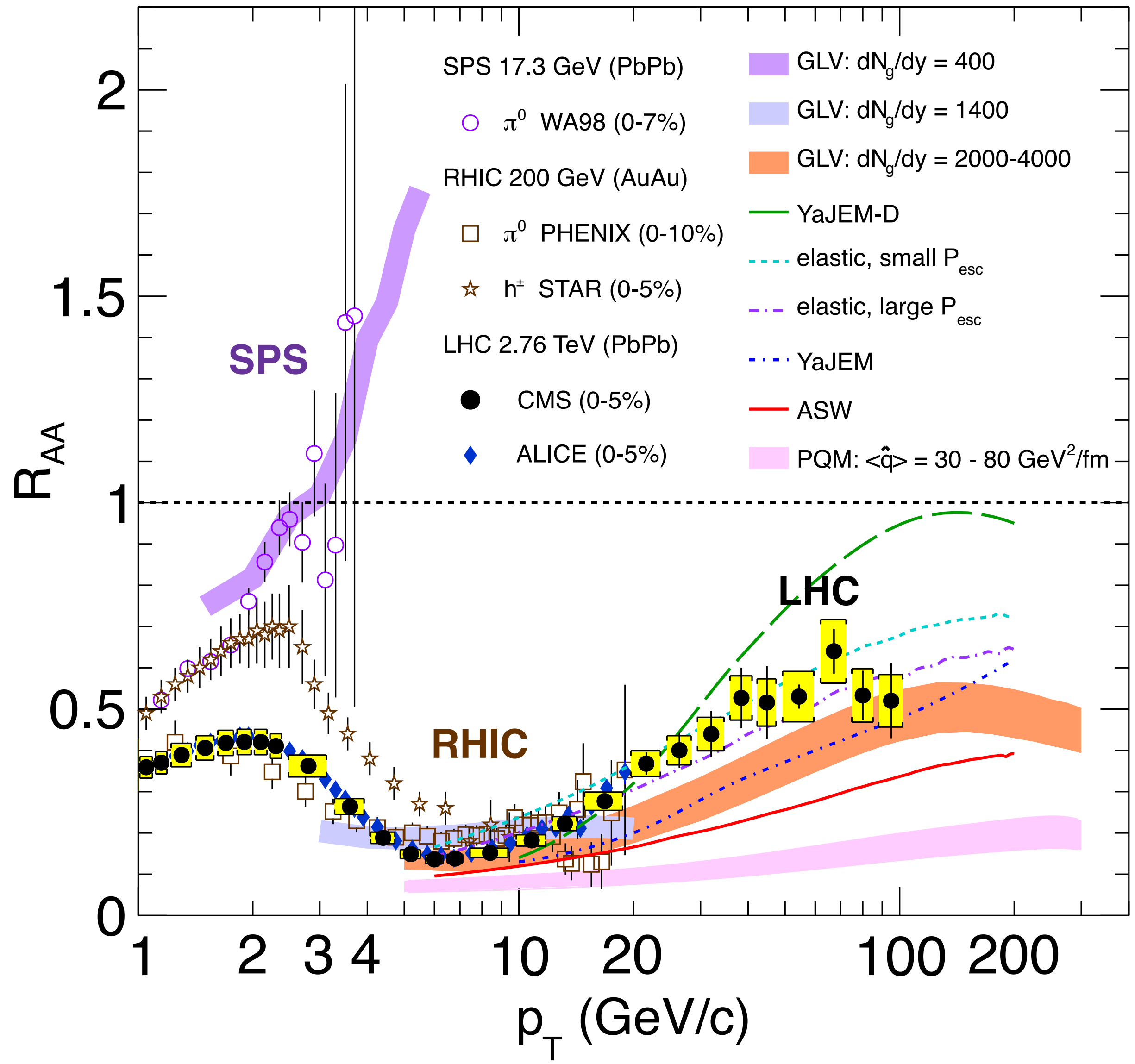
Au–Au → X
($\sqrt{s_{NN}}$ = 200 GeV)

Dihadron Correlations



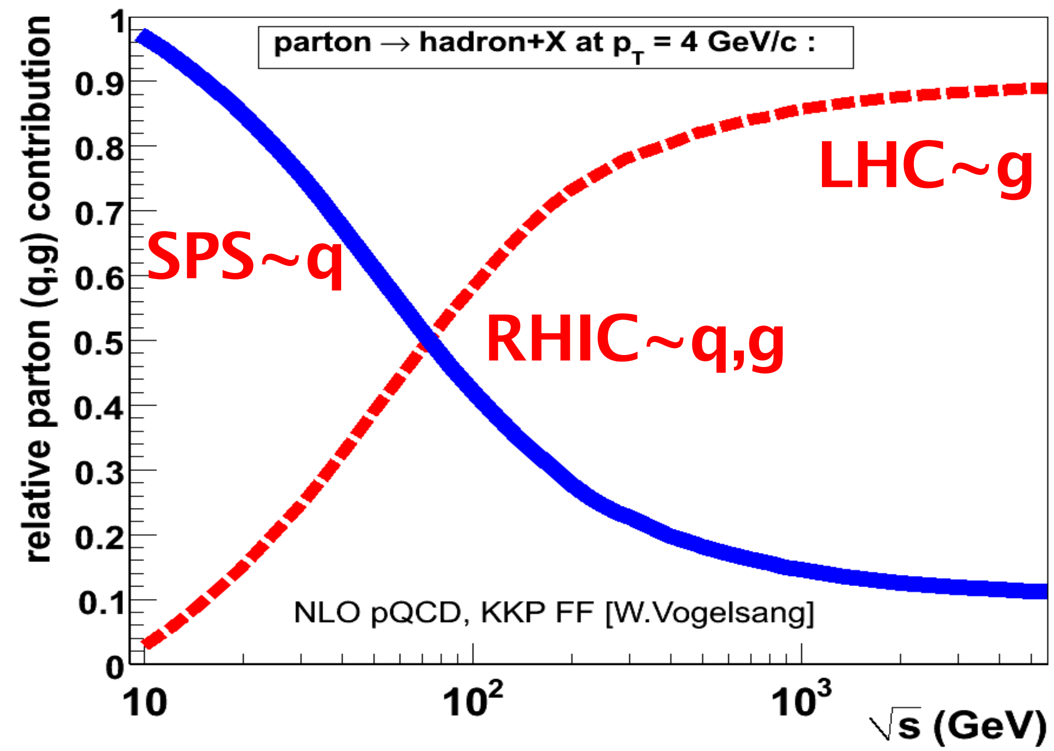
- Two peaks in angular distribution of hadron–hadron correlations
  - near side: hadrons in the same jet
  - away side: hadrons in back-to-back jets
- **Back-to-back correlations disappear in Au–Au collisions**
  - near side correlation remains: “trigger bias”

Hadron suppression vs. $\sqrt{s_{NN}}$



CMS, EPJ C 72 (2012) 1945

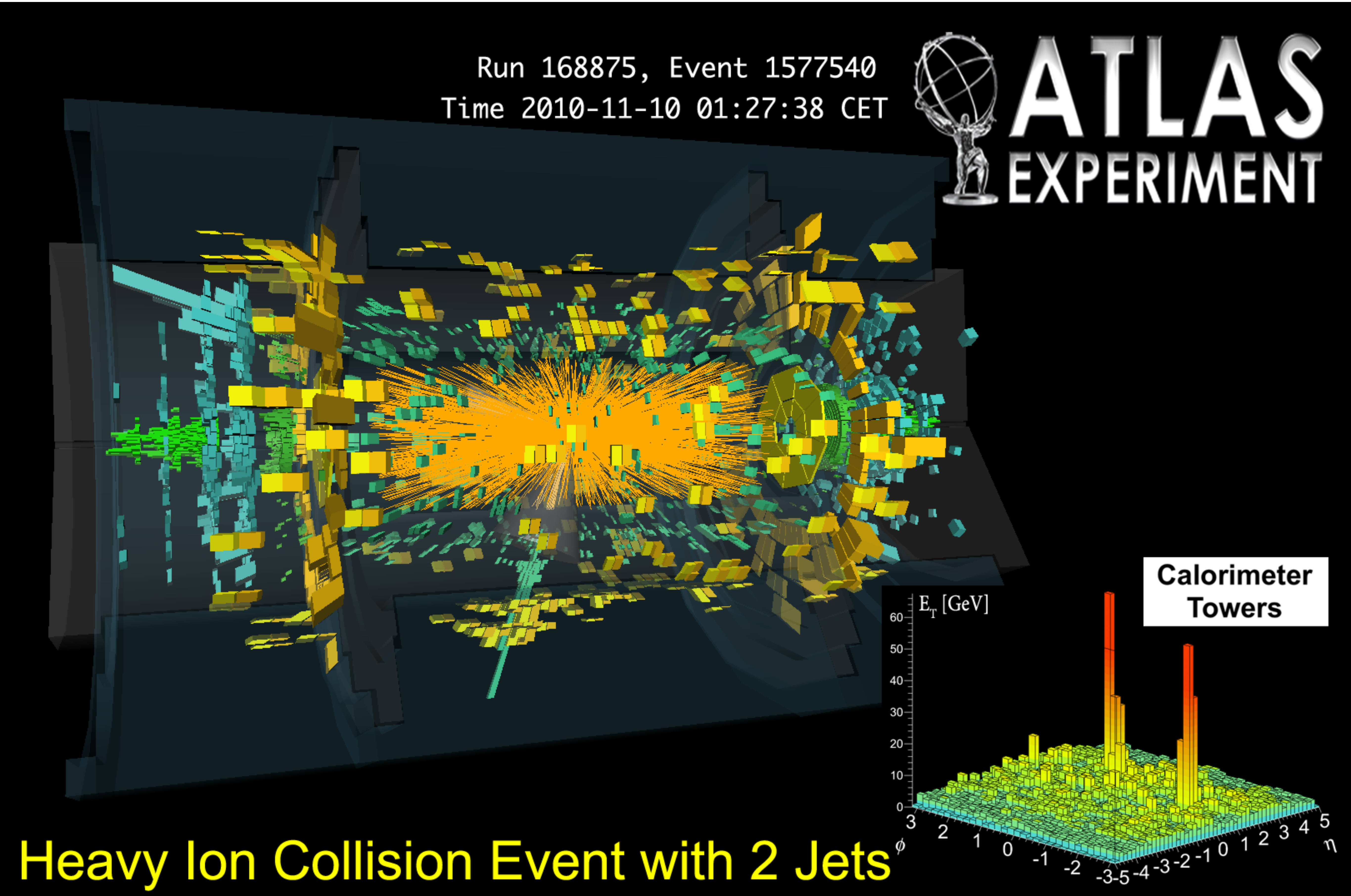
gluons more important at LHC



p_T = 5 GeV/c, $\sqrt{s}$ = 10-5500 GeV

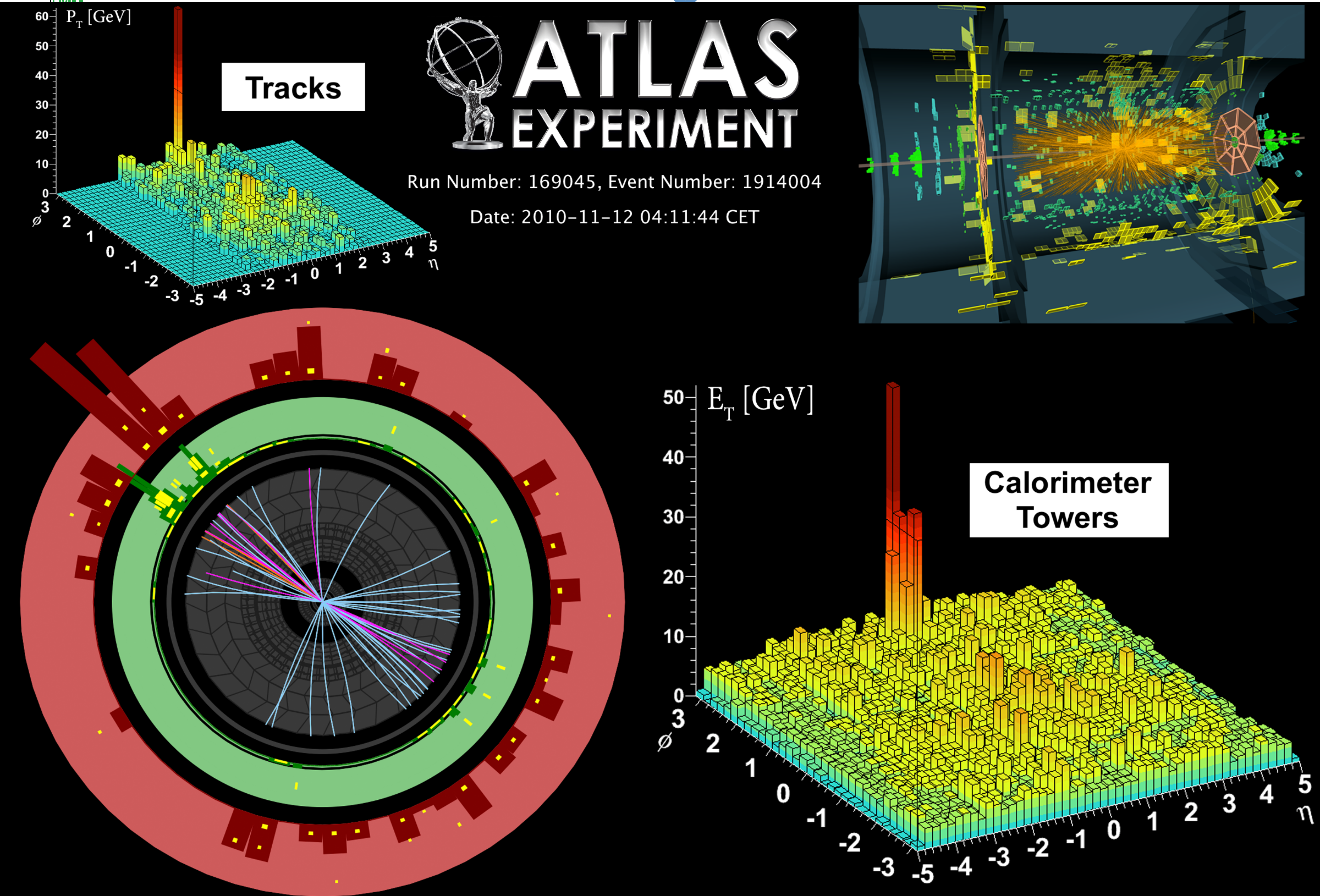
- Suppression increases with $\sqrt{s_{NN}}$
- SPS data at $\sqrt{s_{NN}}$ = 17.3 GeV consistent with unity
- Onset of suppression close to $\sqrt{s_{NN}}$ = 20 GeV
- LHC: increase of R_{AA} at high p_T though still strong suppression at 100 GeV

Jets at the LHC

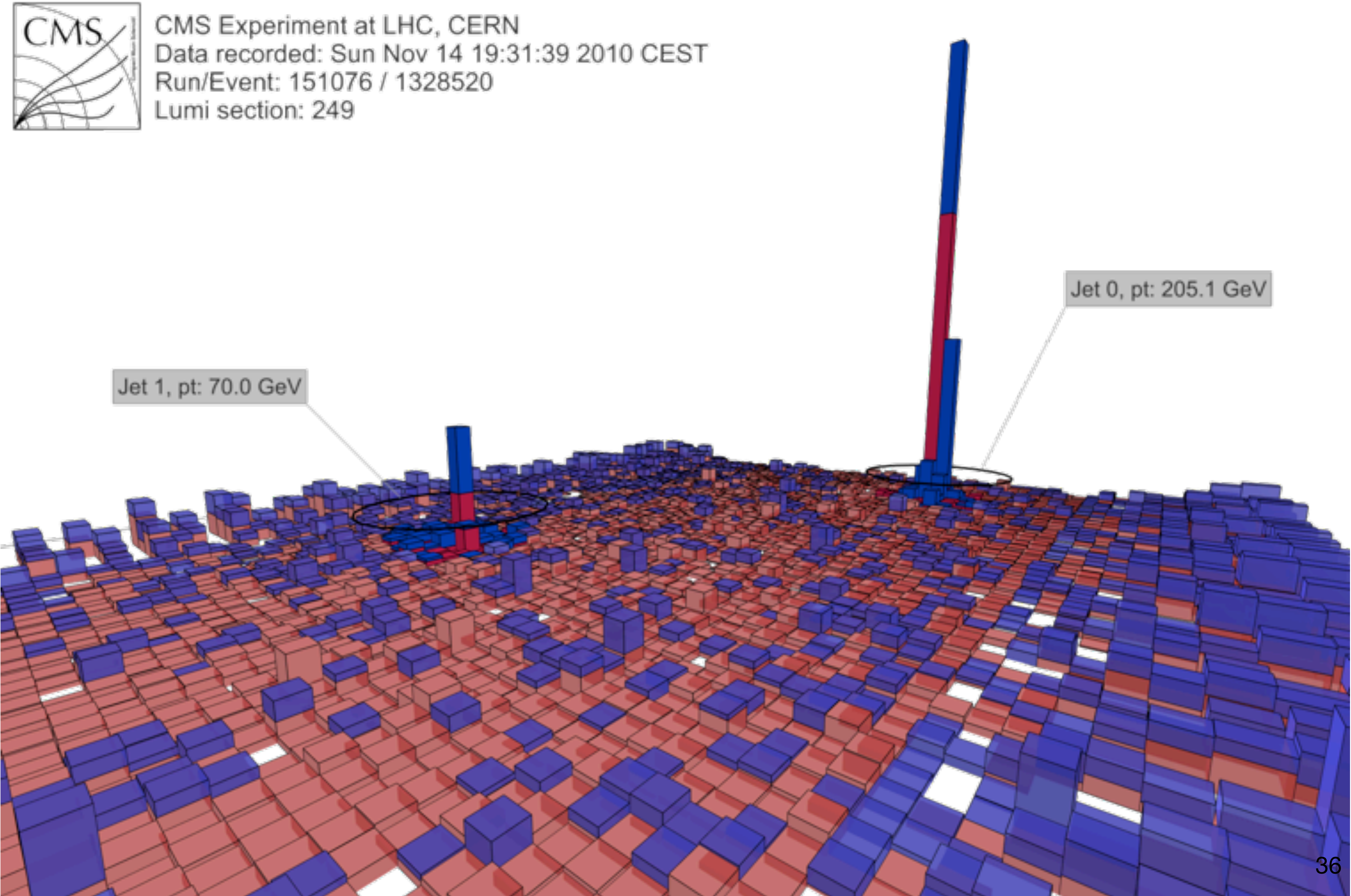


Heavy Ion Collision Event with 2 Jets

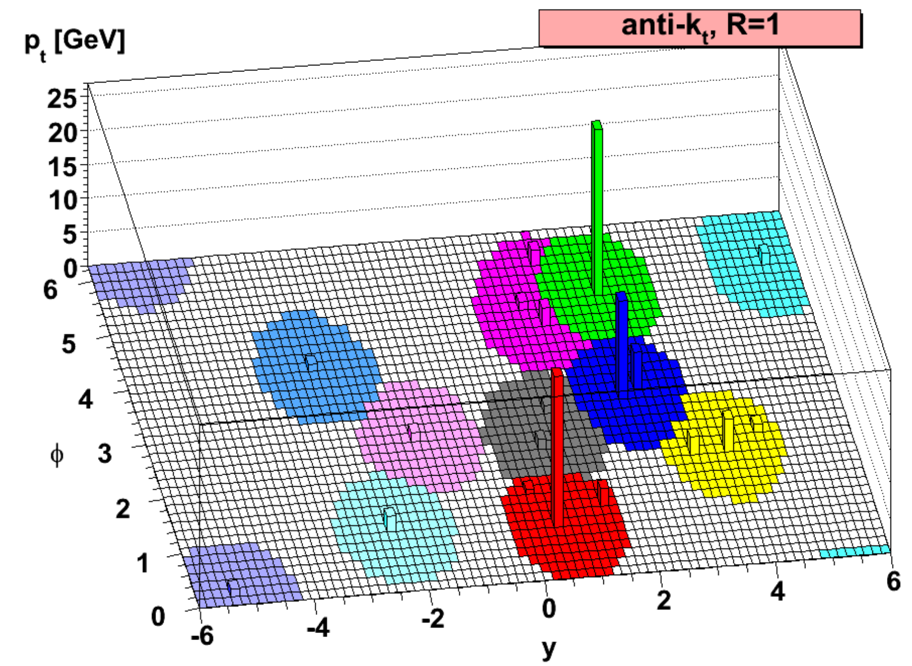
Jet Quenching at the LHC



Jet Quenching at the LHC

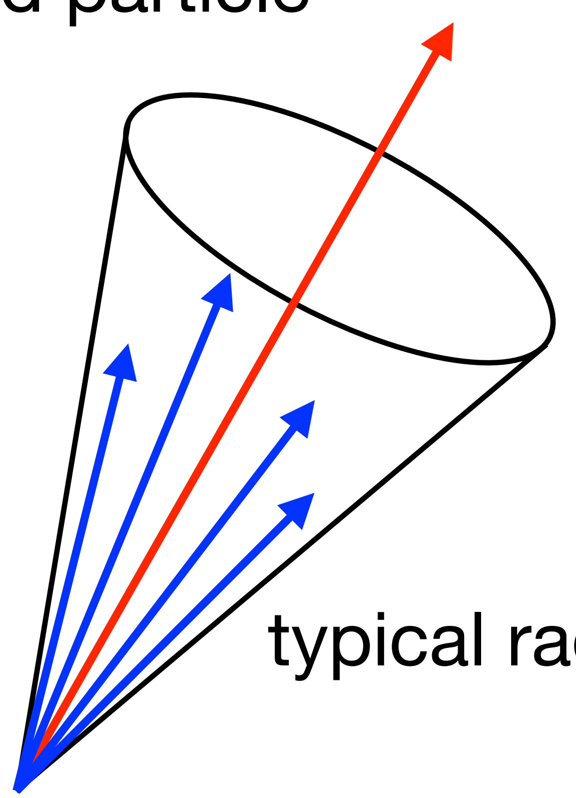


Finding Jets



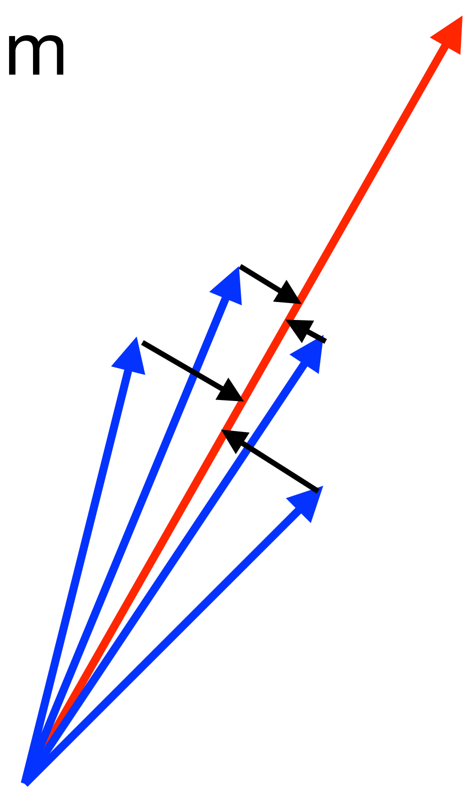
- Measure final state hadrons
- Goal: find the initial parton energy and direction
- Cluster energy deposited in calorimeters
- Two classes of jet clustering algorithm
  - cluster based on proximity in space (cone algorithm)
  - cluster based on proximity in momentum (k_T, anti-k_T algorithm)

search in cone with $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ around seed particle



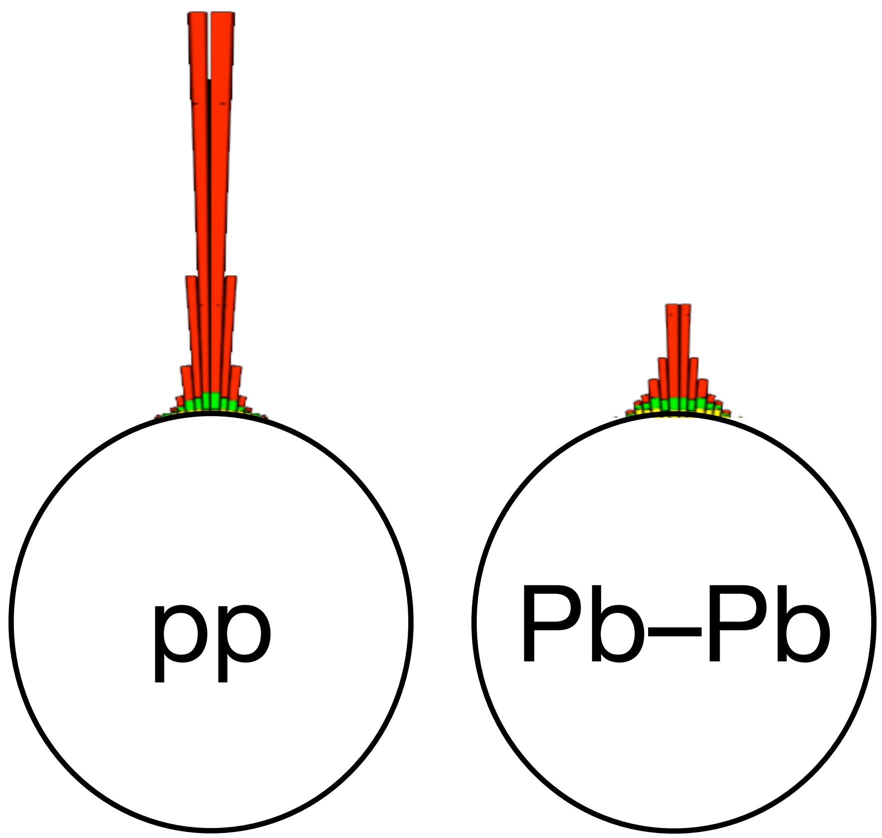
typical radii: 0.3–0.5

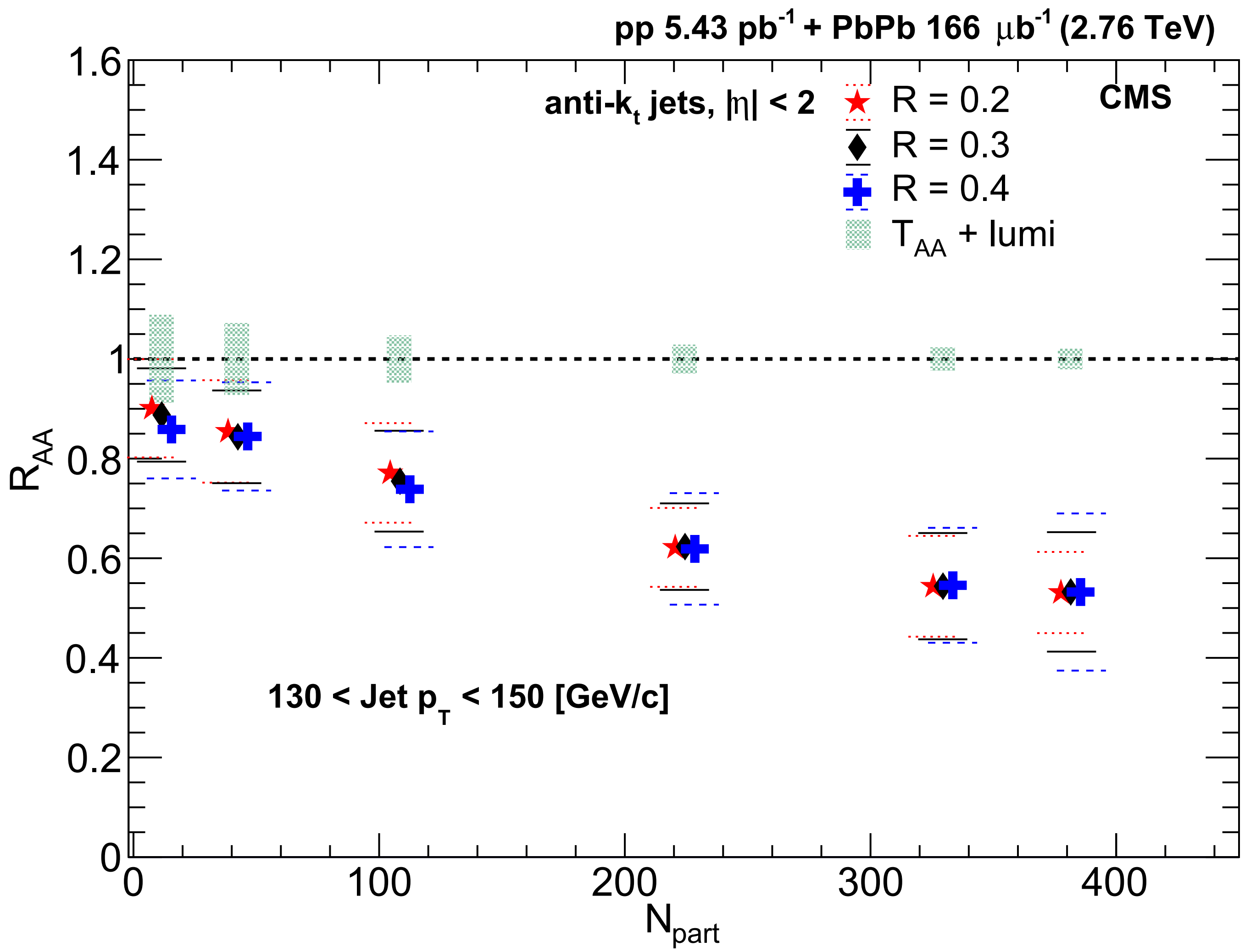
recombine particles close in momentum



Jet R_{AA}

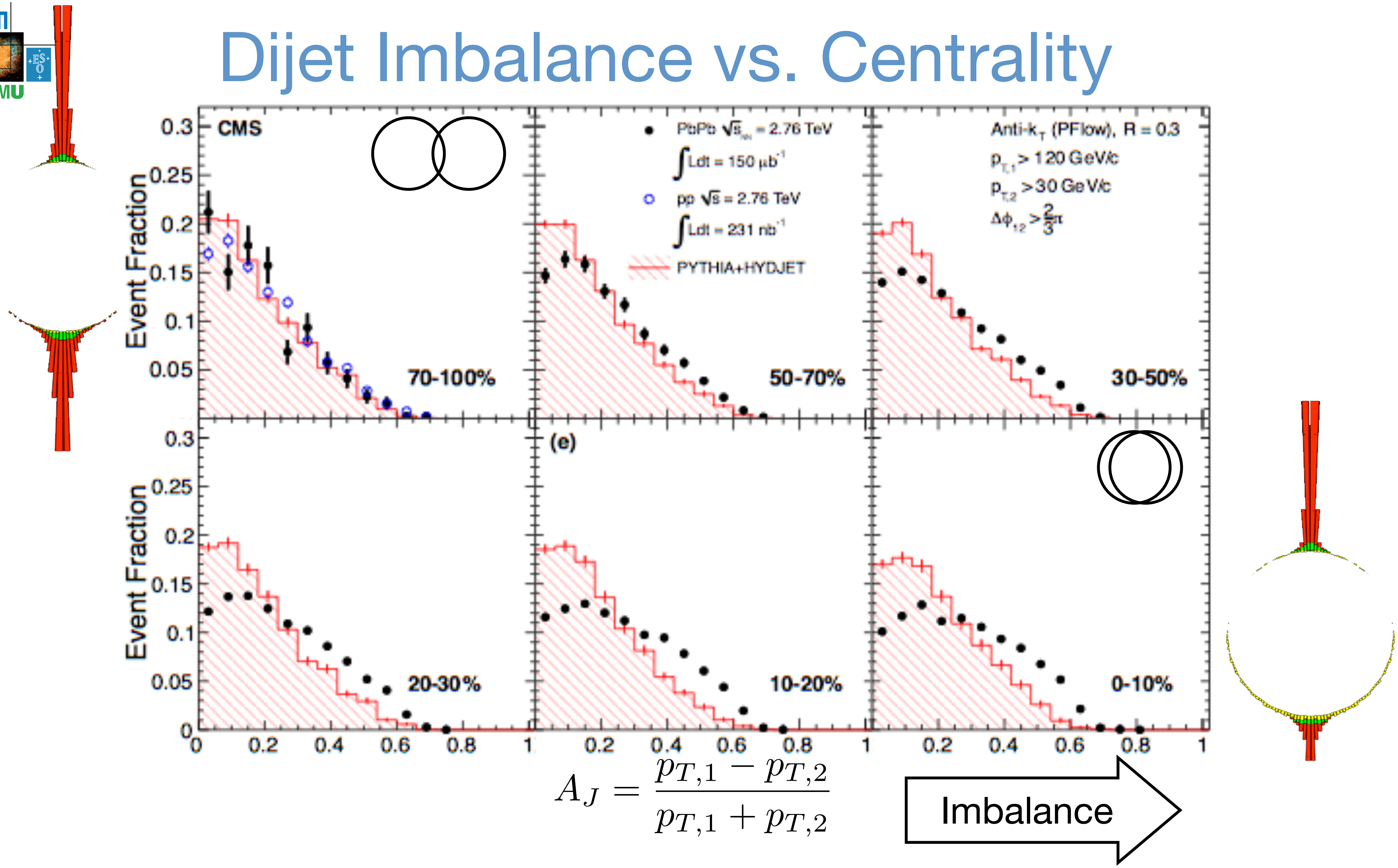
- **Strong suppression of jets**
  - p_T(jet) > 130 GeV
- Energy loss of light quarks and gluons





CMS HIN-15-003
arXiv:1609.05383

Dijet Imbalance vs. Centrality

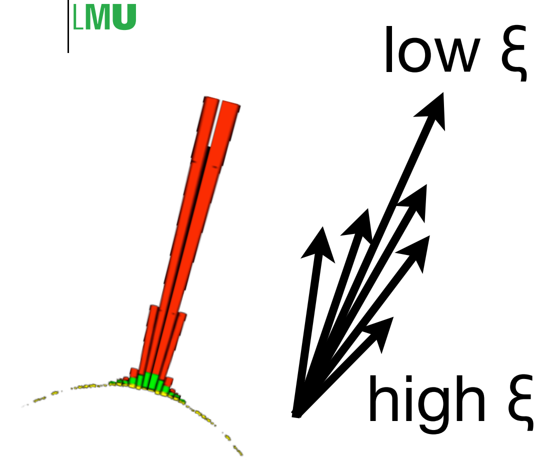


$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

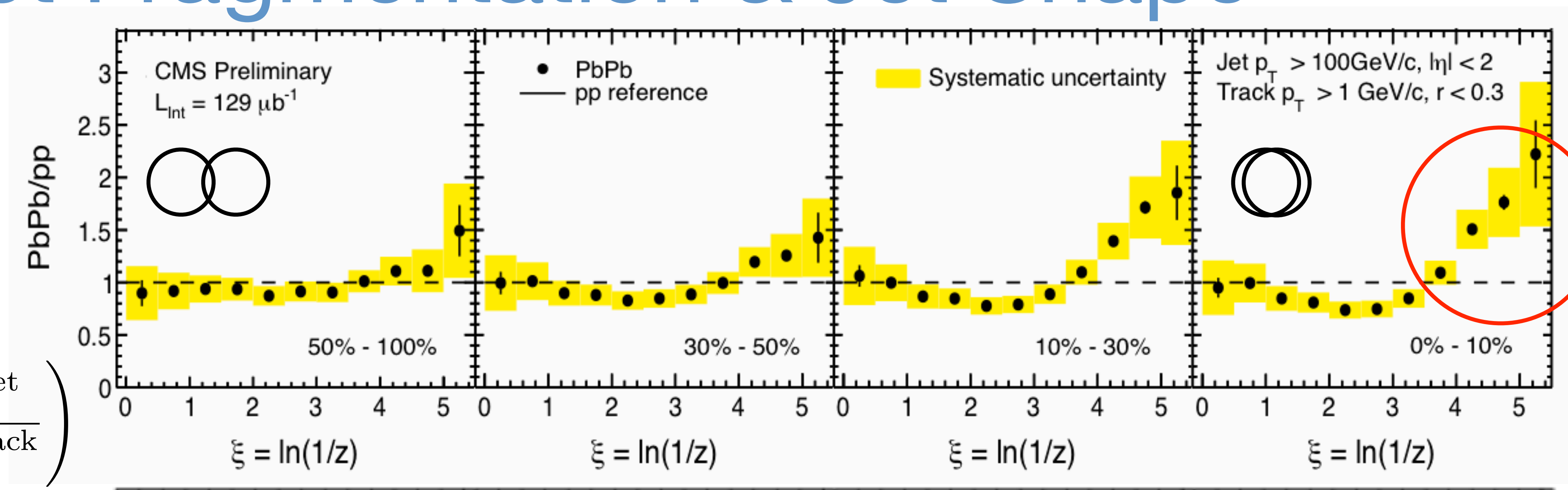
- **Strong modification of the dijet asymmetry**
  - more dijets with large asymmetry
  - surface bias: leading jet is quenched less → larger asymmetry

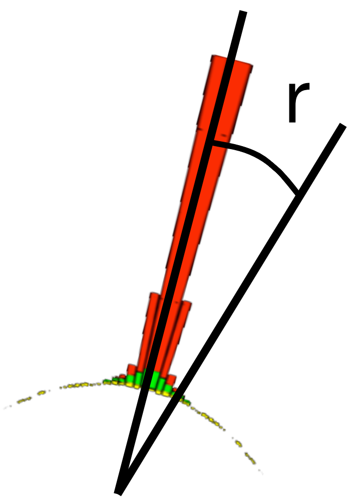
CMS, PLB 712 (2012) 176

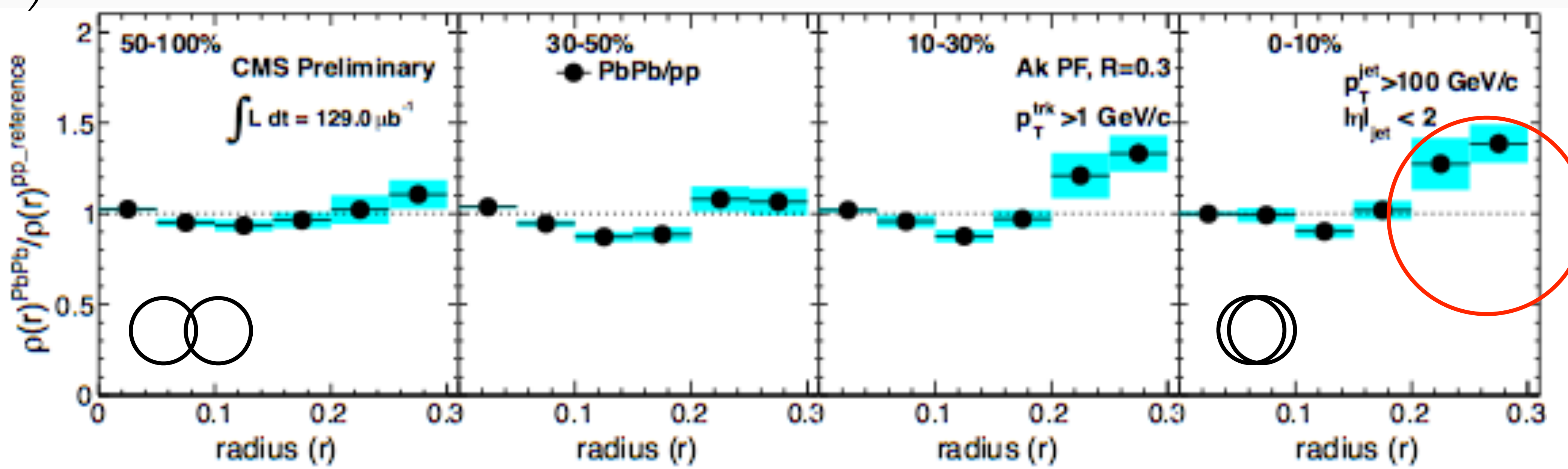
Jet Fragmentation & Jet Shape



$$\xi = \ln\left(\frac{1}{z}\right) = \ln\left(\frac{p^{\text{jet}}}{p_{\parallel}^{\text{track}}}\right)$$





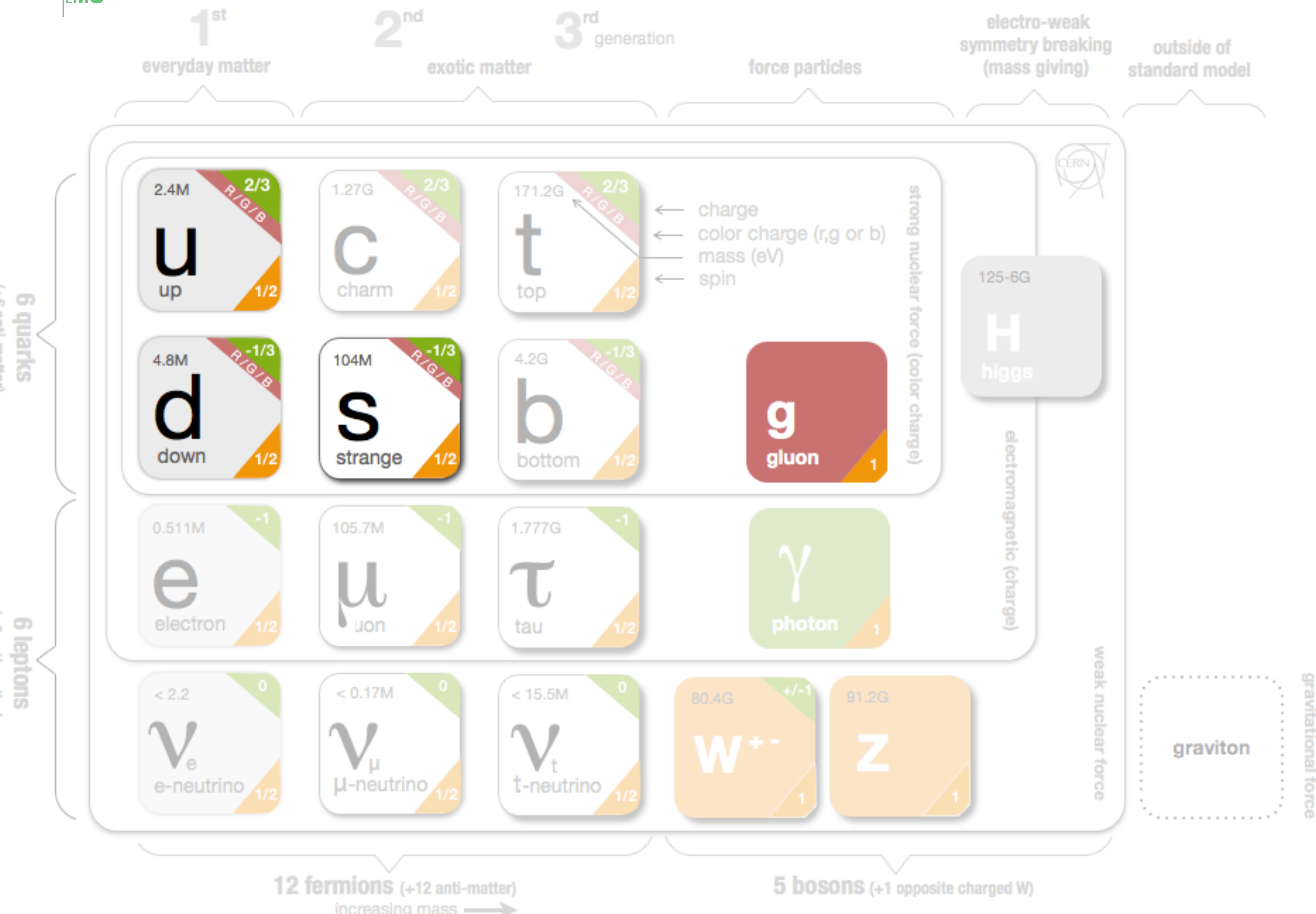


- **Excess of low-p_T particles (high ξ) and long distance from the jet axis**
- Depletion at intermediate p_T and distance from the jet axis
- No modification at high p_T (low ξ) and close to the jet axis

CMS PAS HIN-12-013

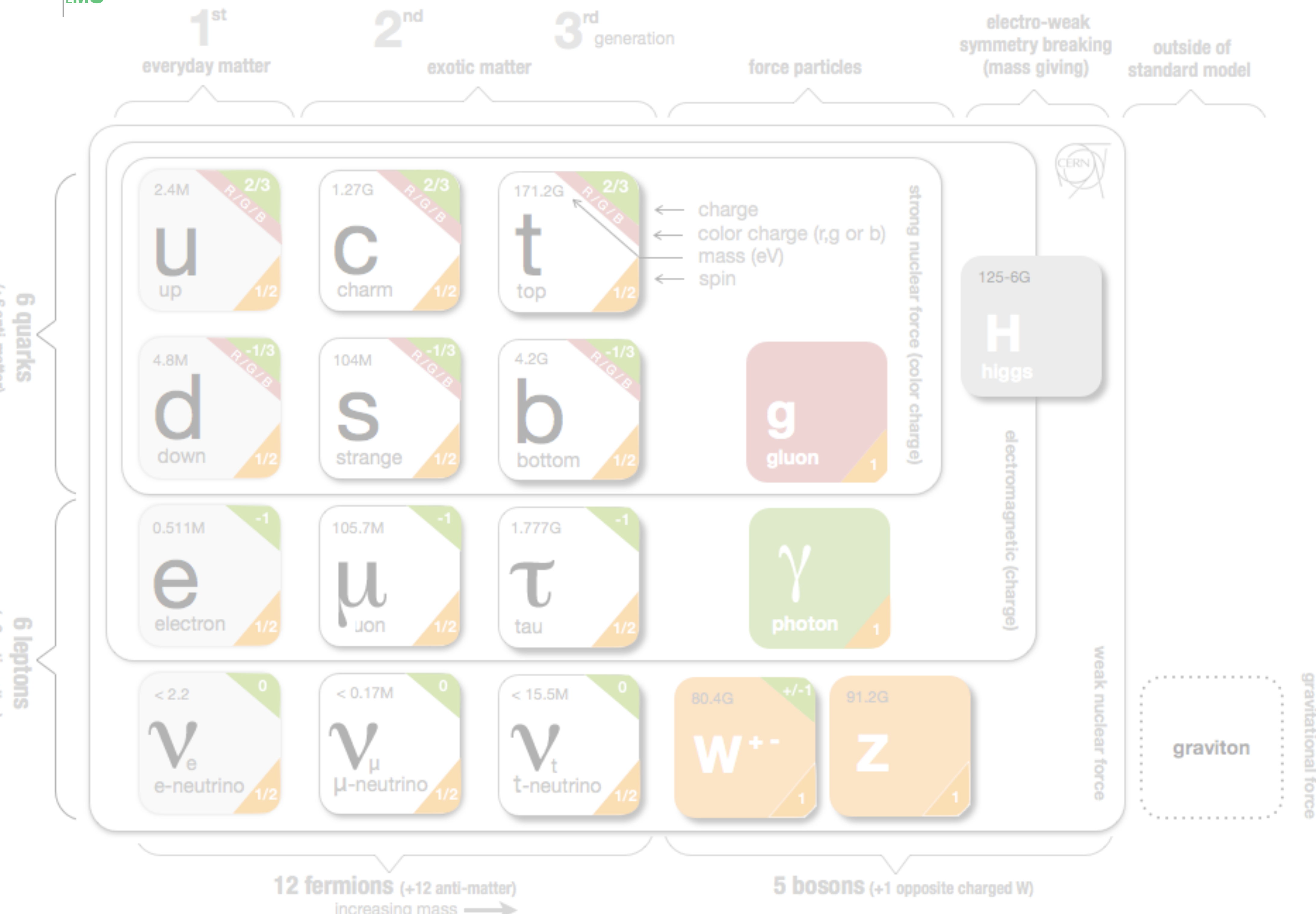
Open Heavy Flavour

Heavy Quarks



from http://www.isgtw.org/spotlight/go-particle-quest-first-cern-hackfest

Heavy Quarks



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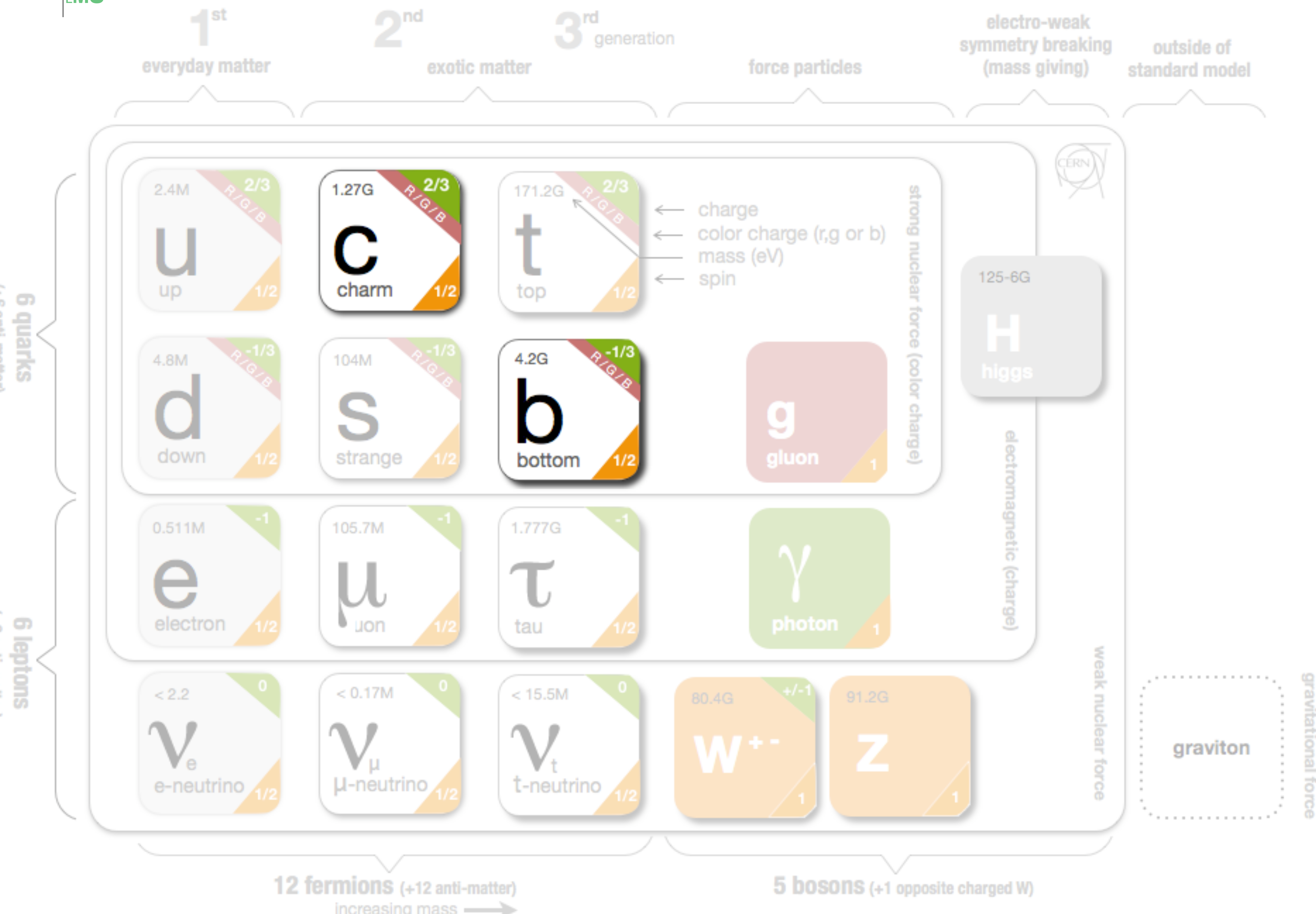

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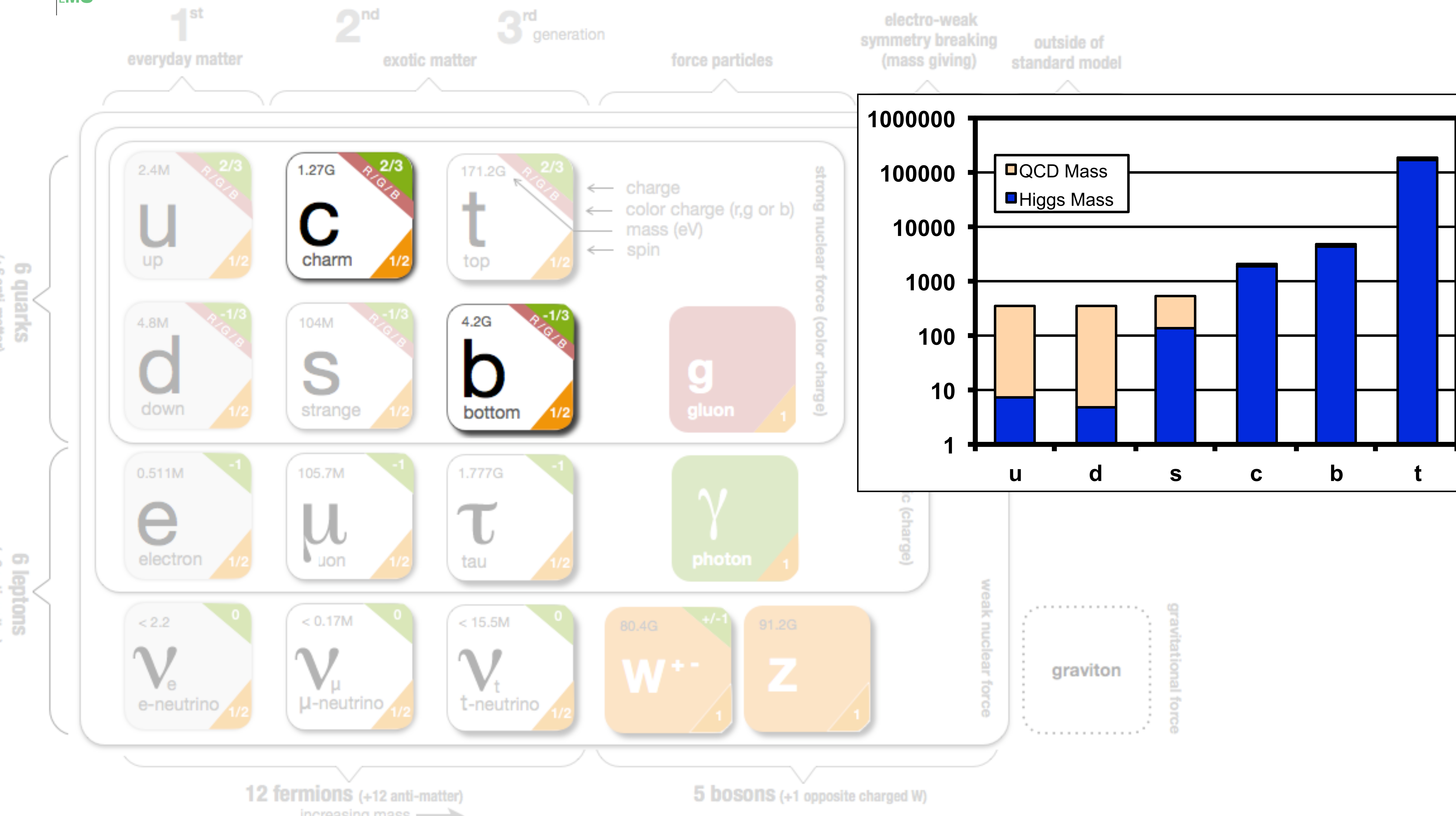

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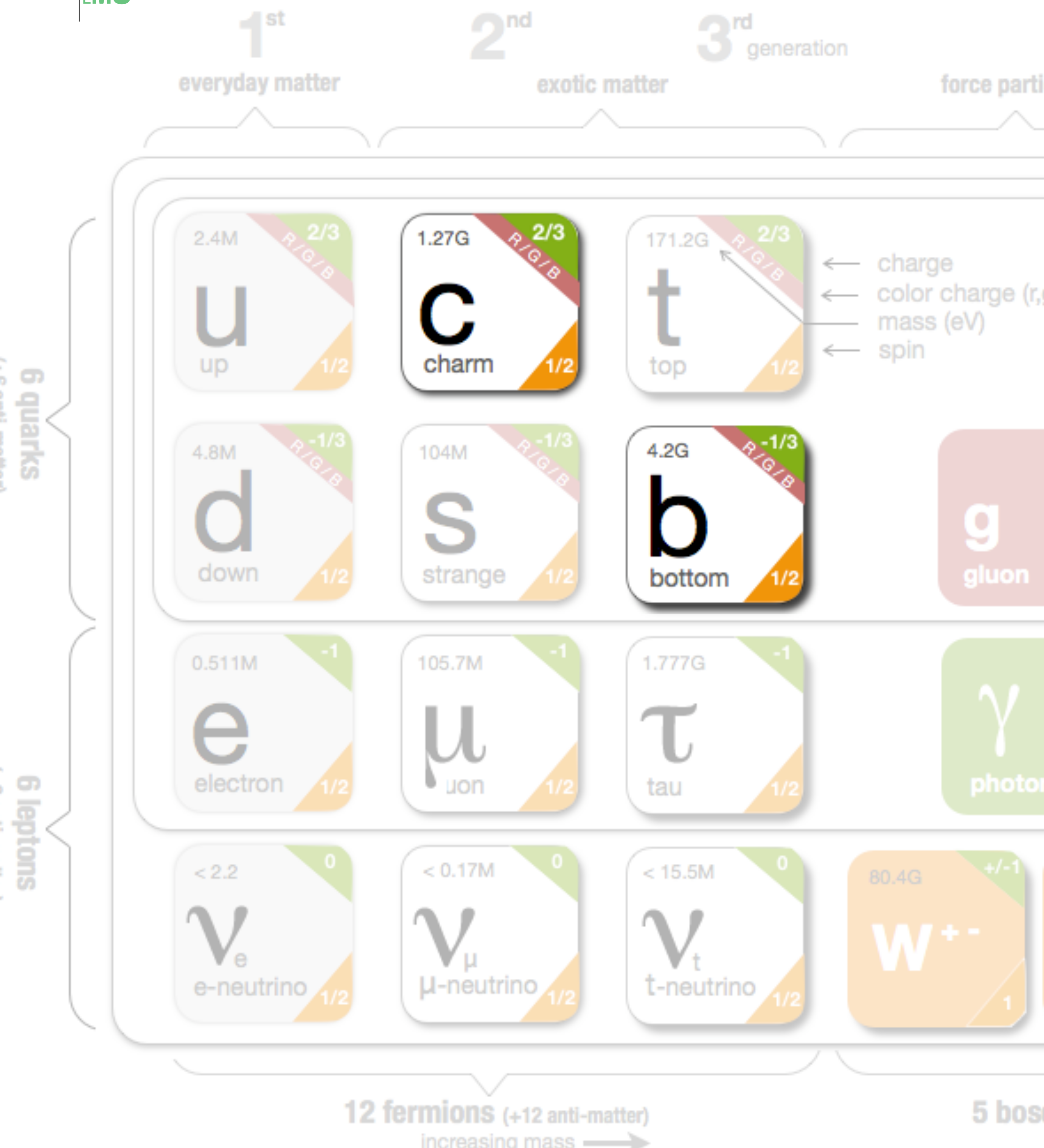
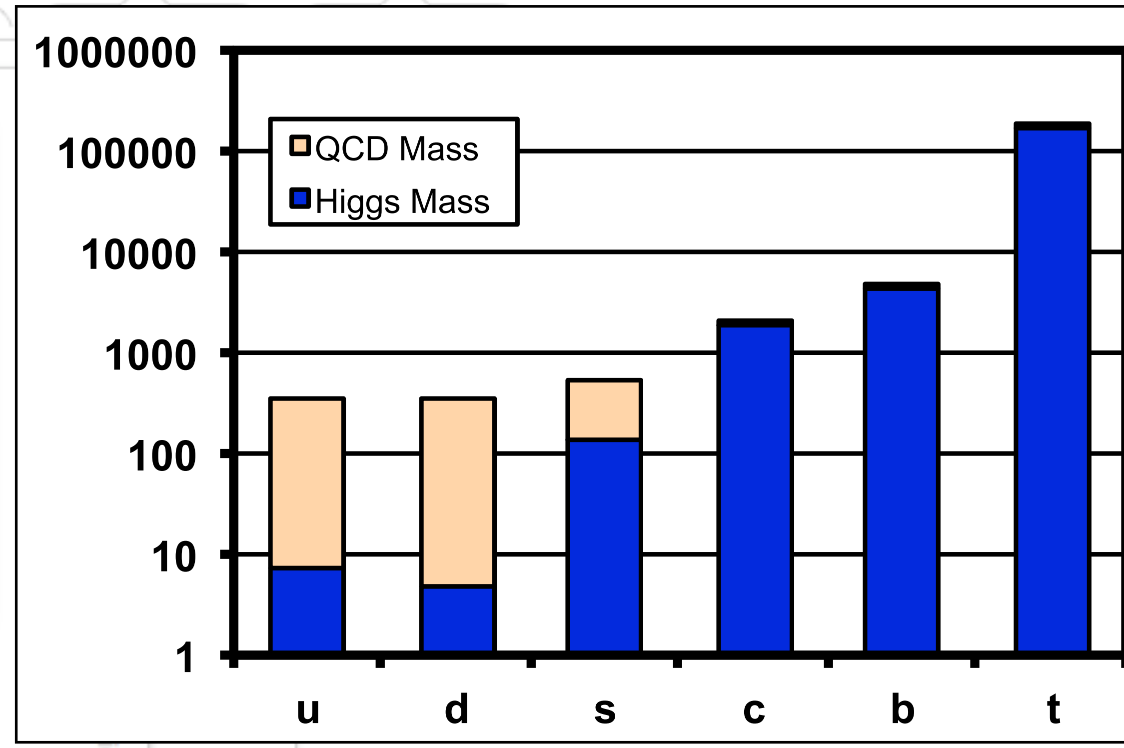


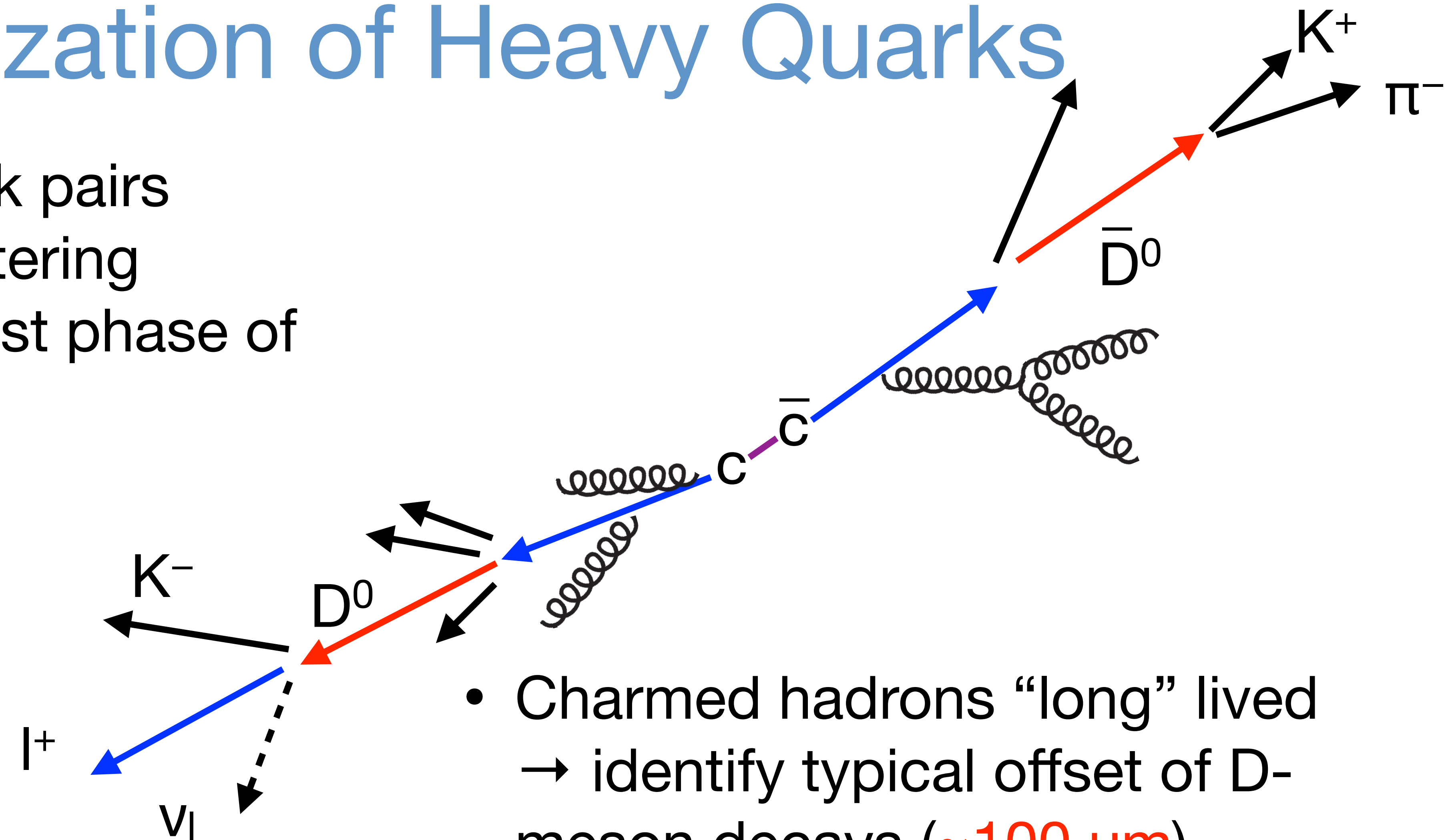
from http://www.isgtw.org/spotlight/go-particle-quest-firs



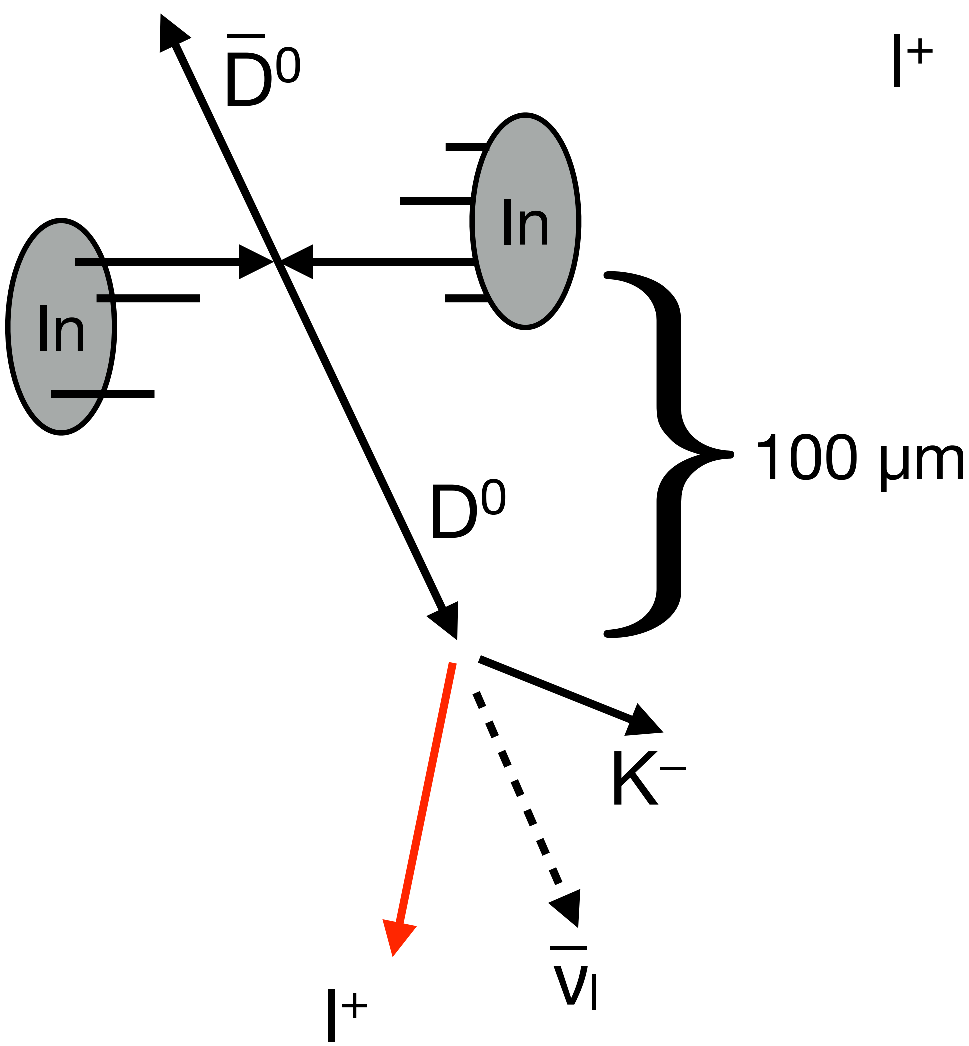
- Charm and Beauty:
  - 200–400× heavier than light quarks
  - not affected by chiral symmetry
  - produced only in initial hard collisions
  - production time: $\tau \sim 1/m_Q \sim 0.05$–$0.15$ fm
  - calculable in pQCD

Hadronization of Heavy Quarks

- Charm quark-antiquark pairs produced in hard scattering processes in the earliest phase of the collisions



- Charmed hadrons “long” lived → identify typical offset of D-meson decays (~100 μm)



$$D^0 \to K^-\pi^+ \quad \text{(hadronic)}$$

$$D^0 \to K^-e^+\nu_e \quad \text{(semileptonic)}$$

$$D^{*0} \to D^0\pi^0 \quad \text{(excited state)}$$

$$\Lambda_c^+ \to pK^-\pi^+ \quad \text{(charmed baryon)}$$

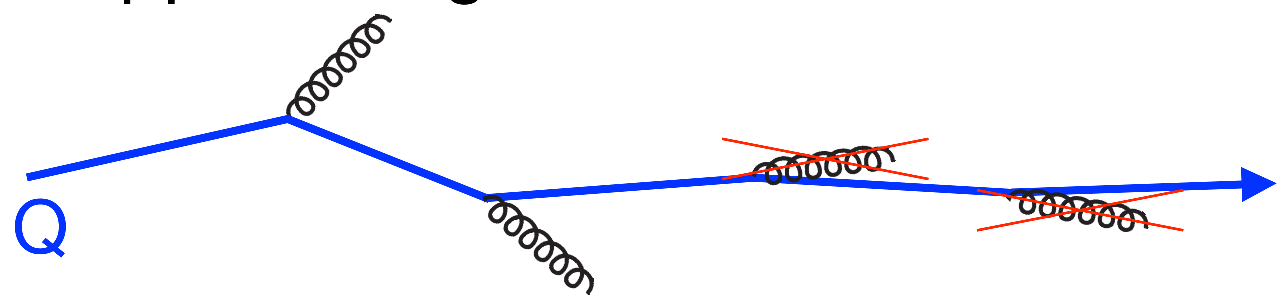
$$B^+ \to \overline{D}^0\mu^+\nu_\mu \quad \text{(semileptonic)}$$

$$B^0 \to J/\psi K^0 \quad \text{(non-prompt charmonium)}$$

Energy Loss of Heavy Quarks

- Radiative energy loss $\Delta E_{\mathrm{rad}}^{\mathrm{LPM}} \propto \alpha_s C_R \hat{q} L^2$

- Dead cone effect suppresses gluon radiation for small angles



$$\omega \frac{dI_{\mathrm{rad},\,Q}}{d\omega\, dk_T^2} = \frac{\alpha_s C_R}{\pi} \frac{k_T^2}{(k_T^2 + \omega^2\theta_0^2)^2} \approx \omega \frac{dI_{\mathrm{rad}}}{d\omega\, dk_T^2} \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2}$$

  - with $\theta_0 = \frac{M_Q}{E_Q} = \frac{1}{\gamma}$
  - and gluon transverse momentum $k_T \approx \omega\theta$

Yu. L. Dokshitzer et al., JPG, 17(1991) 1602
Yu. L. Dokshitzer et al.PLB 519 (2001) 199

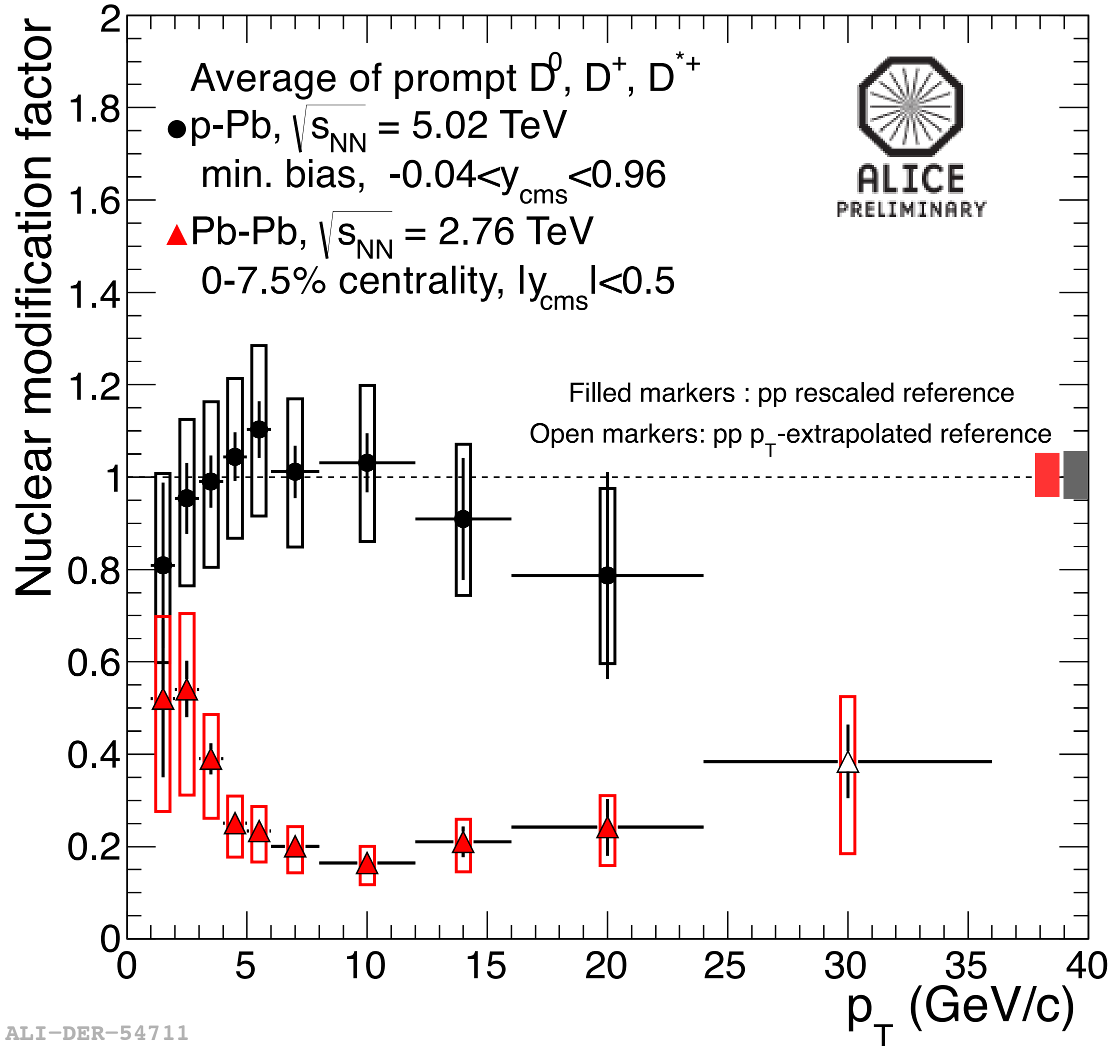
- Mass dependent energy loss:

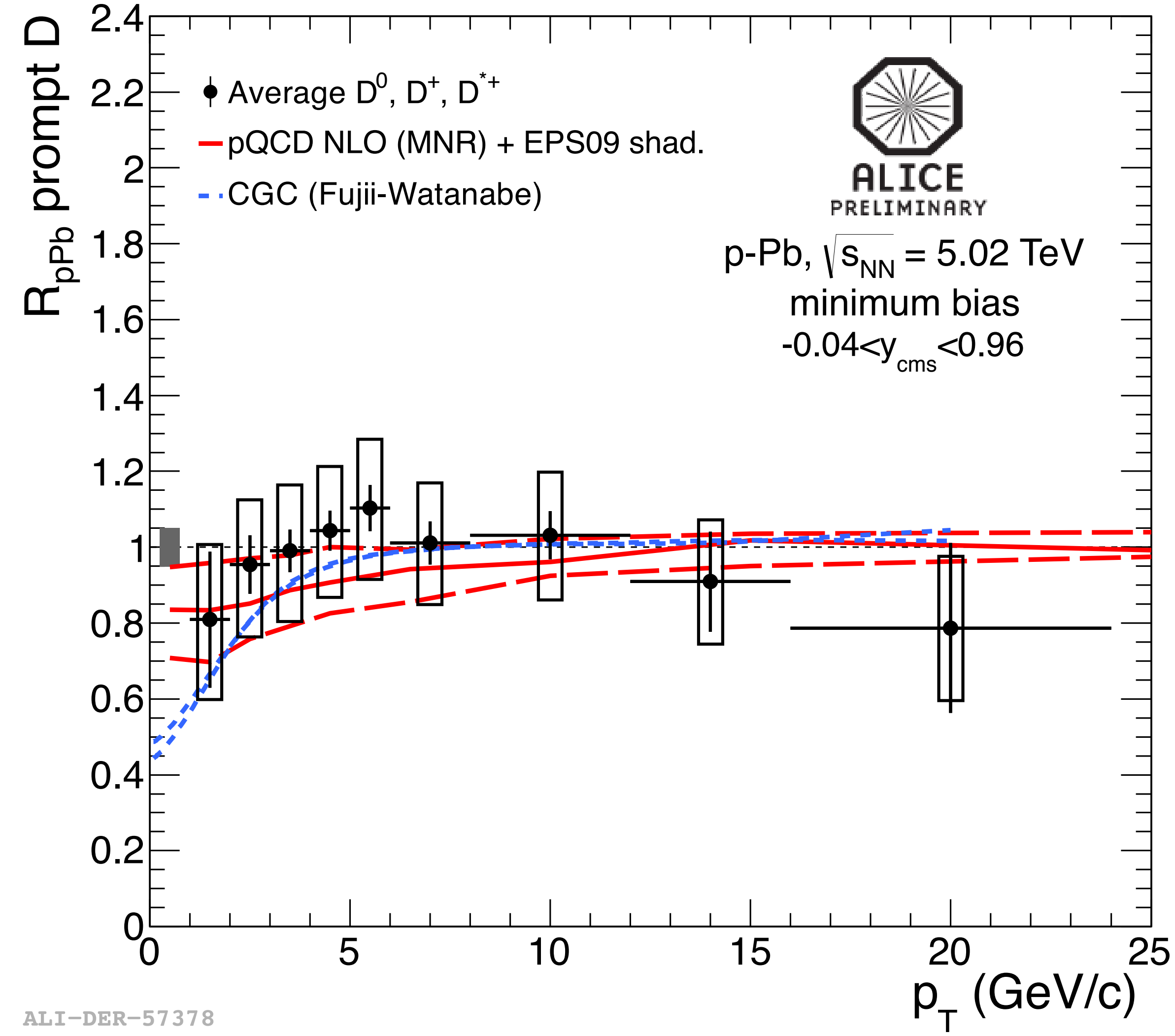
$$\Delta E_g \overset{C_R}{>} \Delta E_q > \Delta E_c > \Delta E_b$$

- Expect mass ordering of suppression:

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

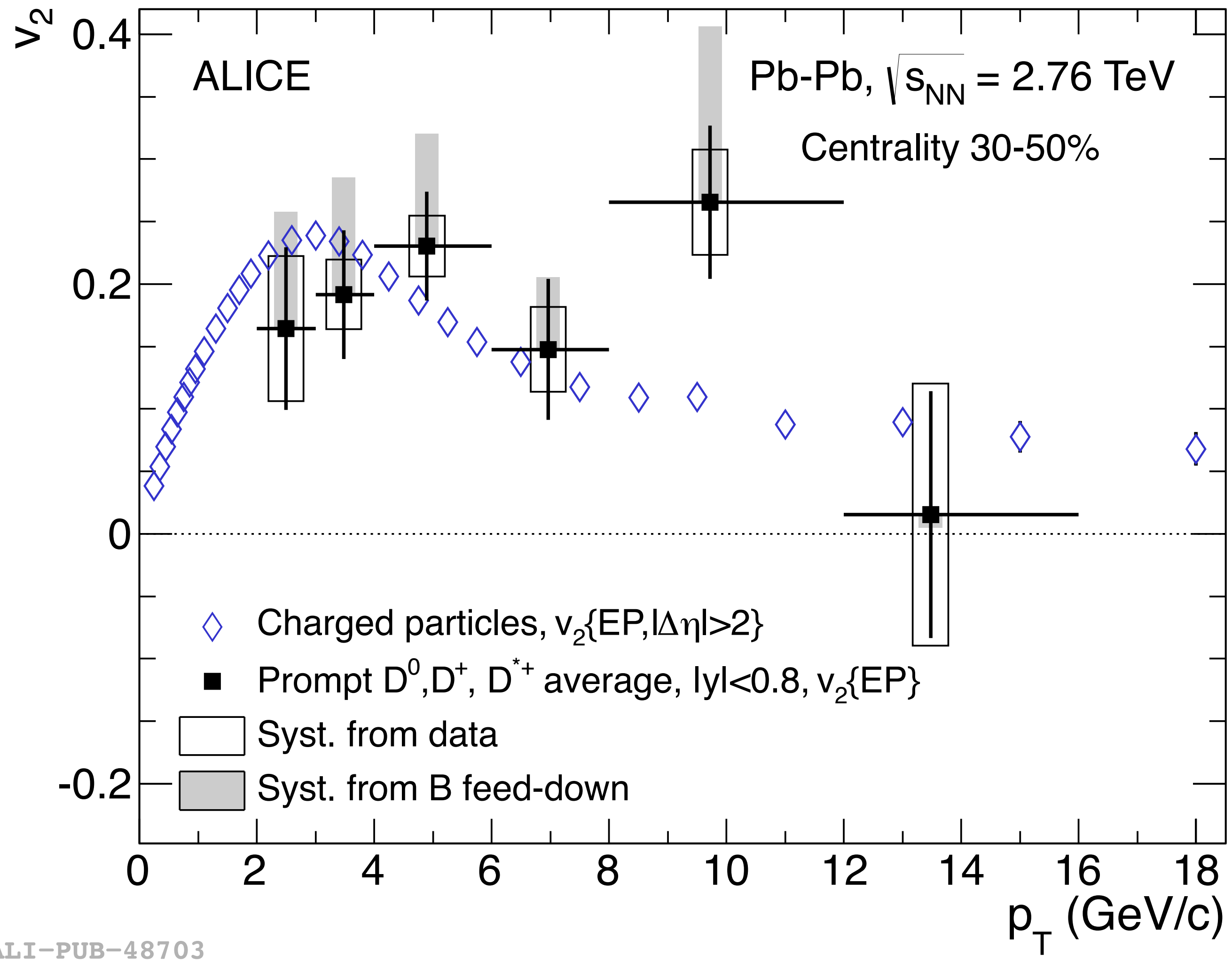
D mesons at the LHC

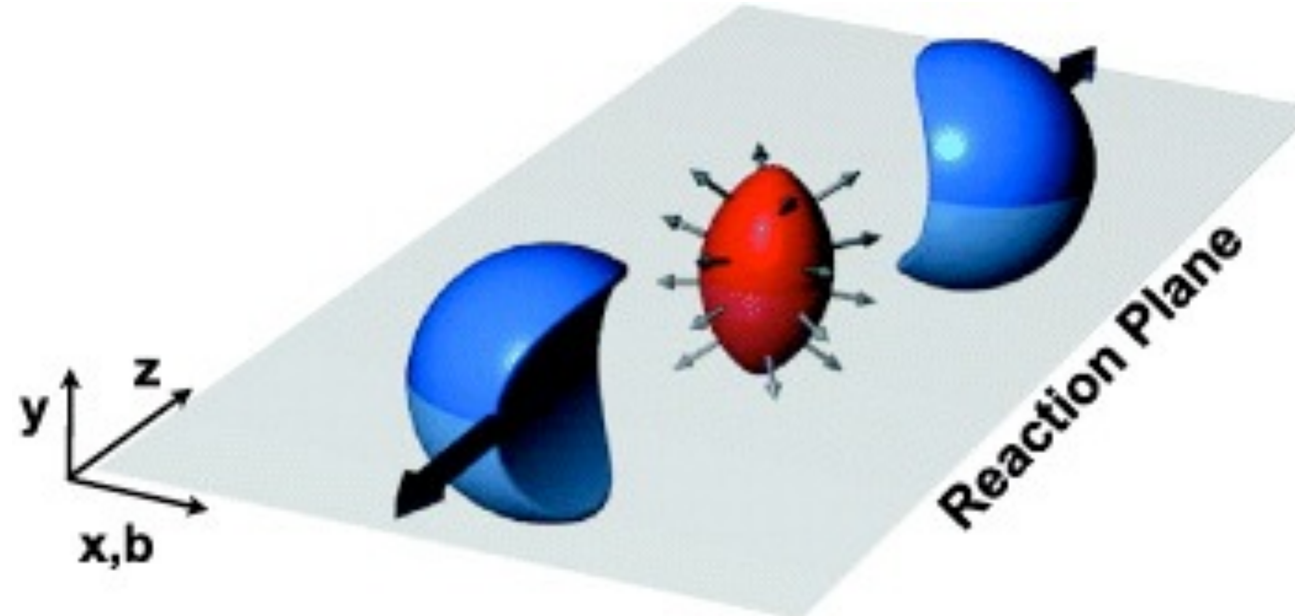




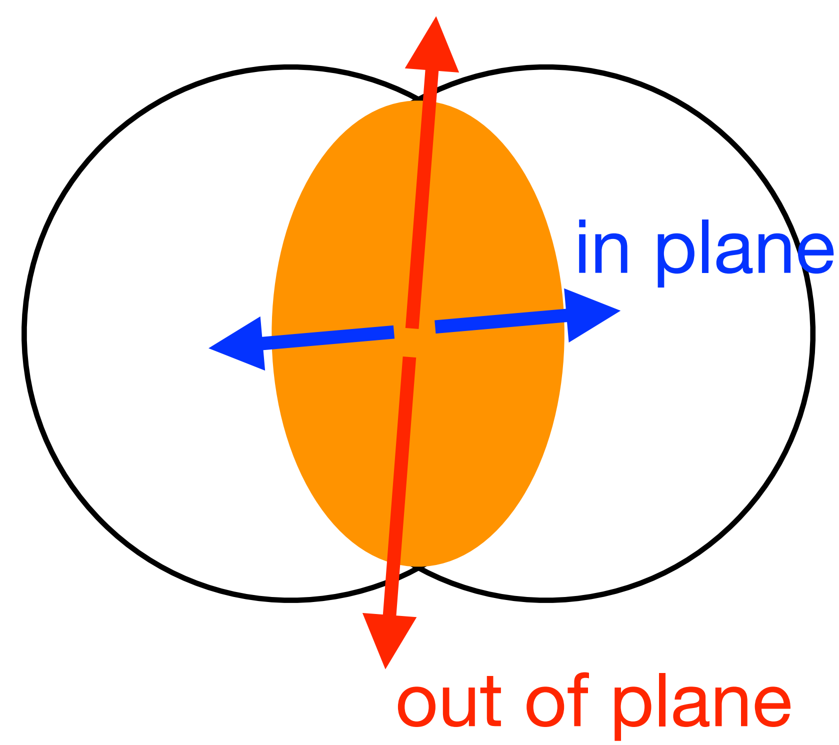
- No suppression in pPb
  - variations in agreement with expected nuclear PDF modifications
- Strong suppression in Pb–Pb is a final state hot medium effect

D meson azimuthal anisotropy

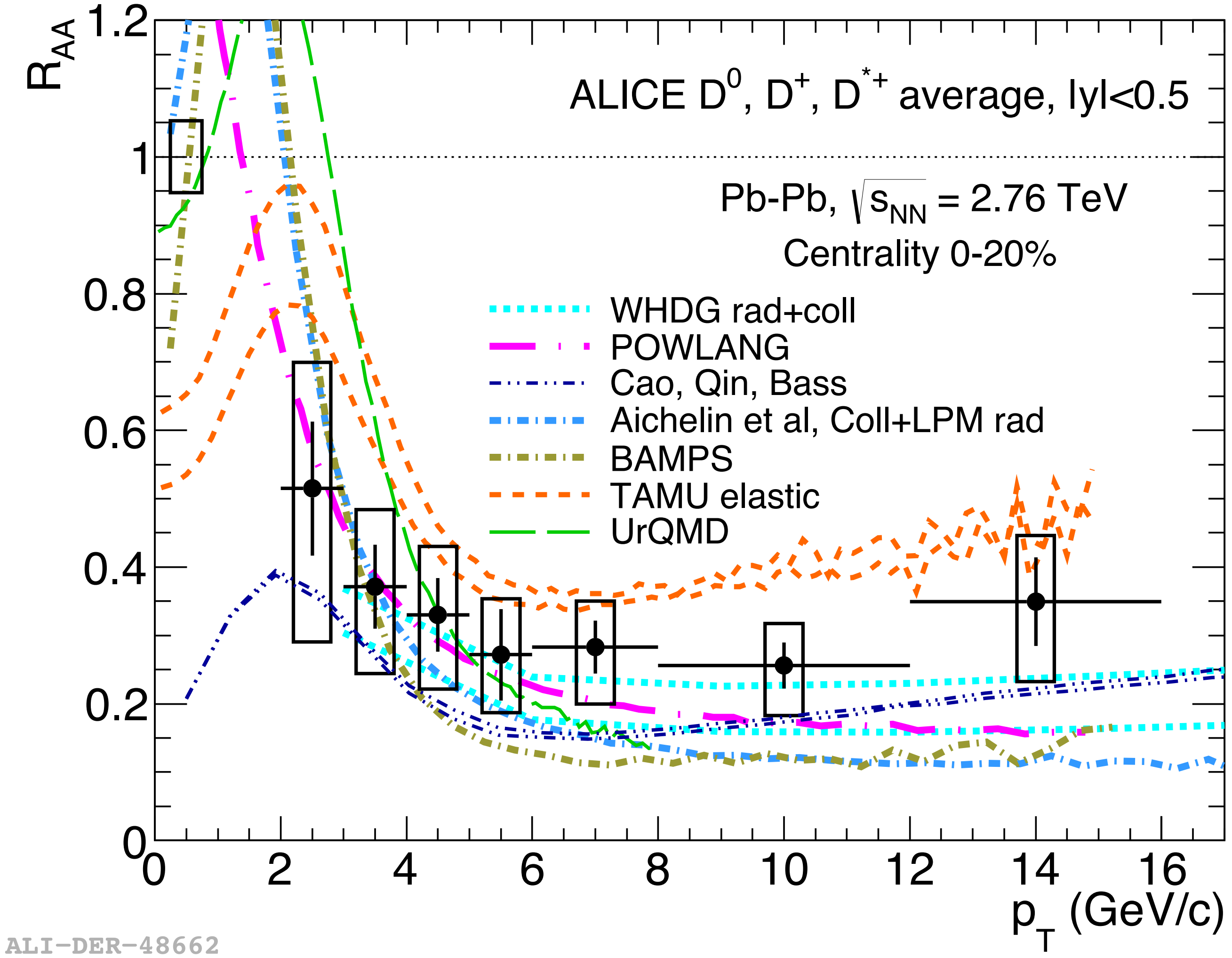


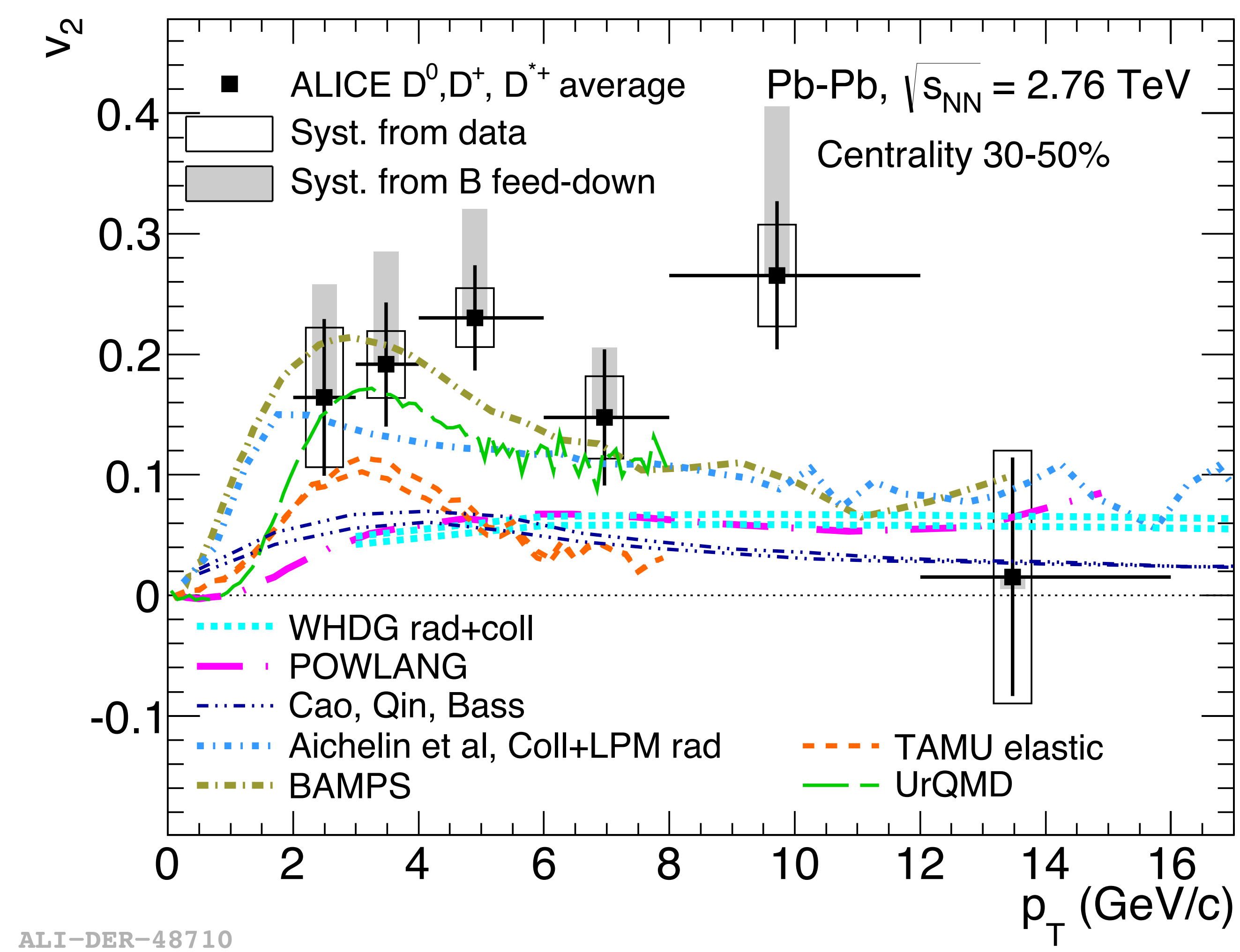


- $v_2>0$:
  more particles emitted in plane than out of plane
- Strong azimuthal anisotropy of D mesons
  - Comparable to light hadrons
- Low p_T: collective motion
- High p_T: path length dependent suppression



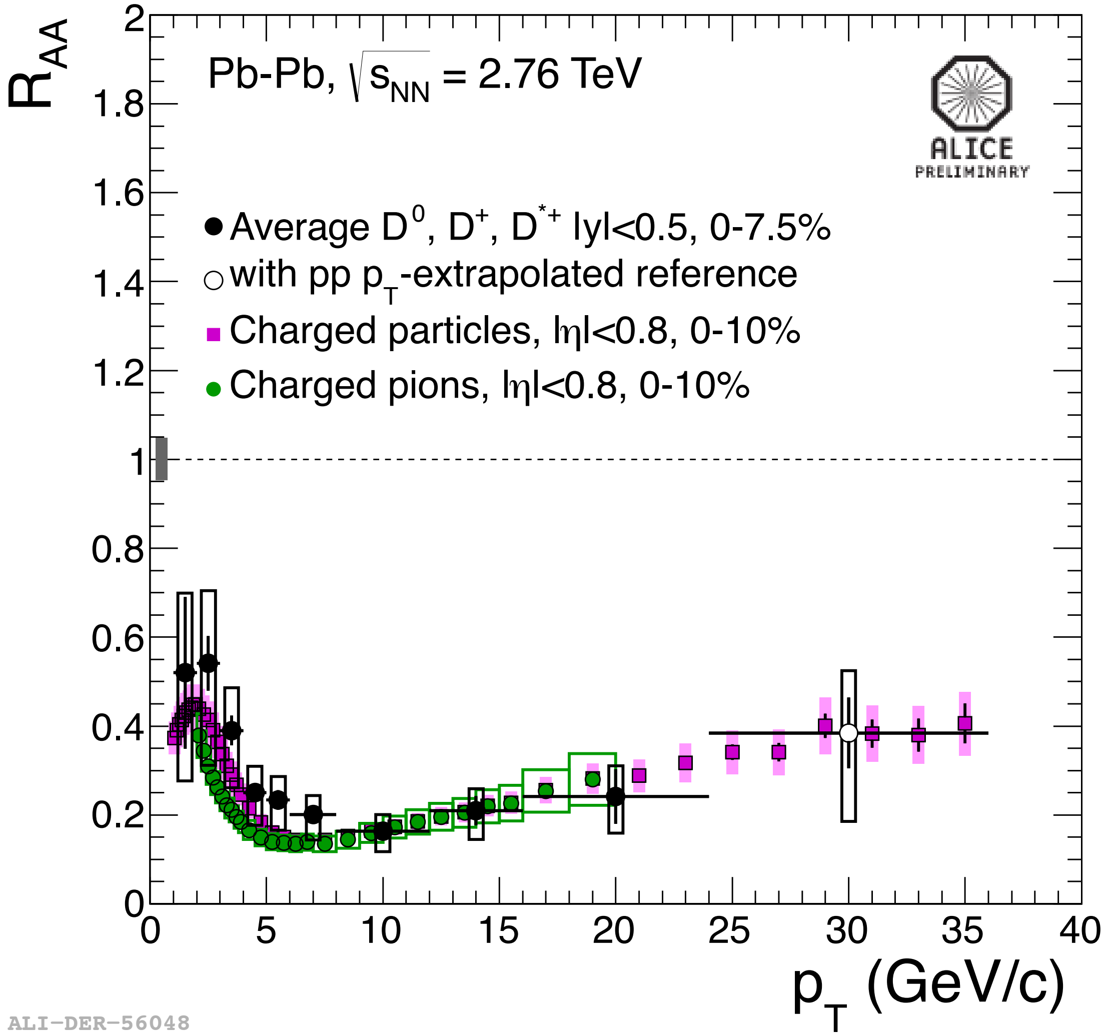
Model Comparison for D mesons

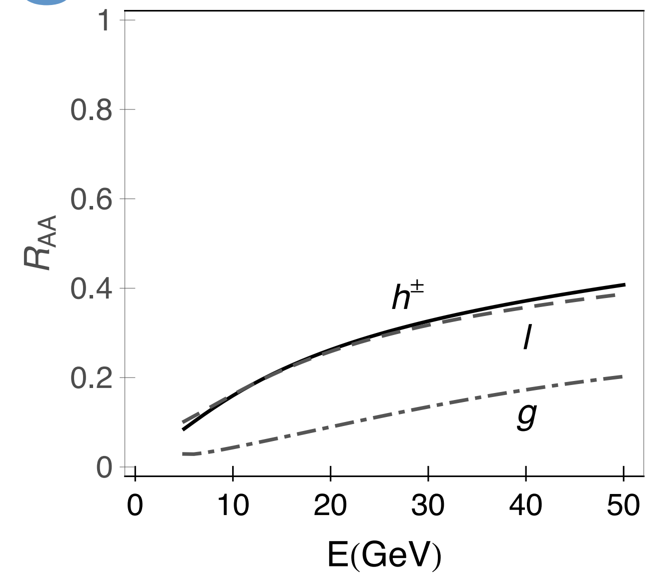


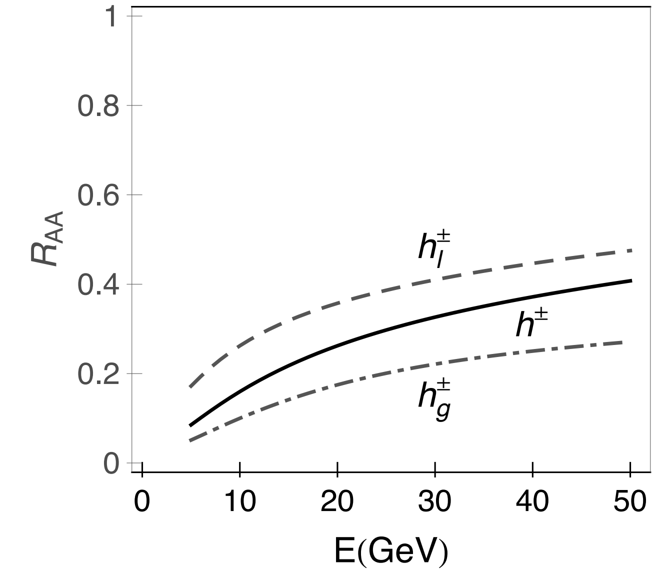


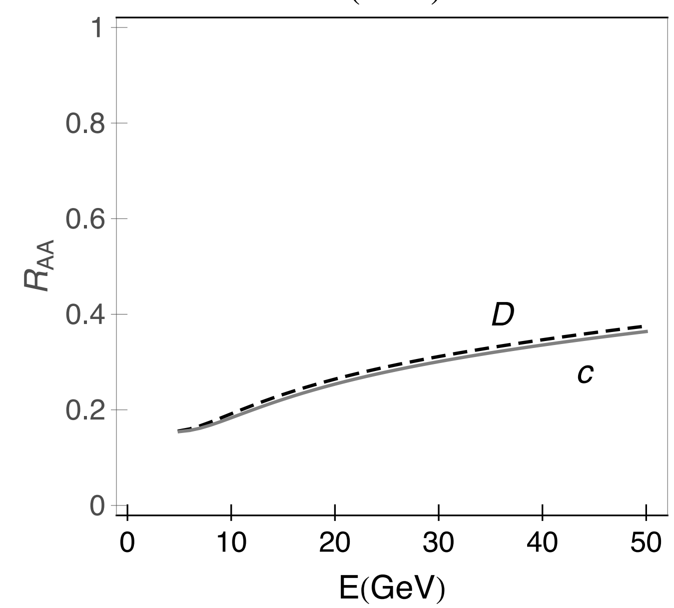
- Need radiative & collisional energy loss to describe R_{AA}
- Radiative energy loss does not produce enough v_2, challenge to models
- Charm quarks interact strongly with the medium and participate in the collective motion

Heavy vs. light flavour









M. Djordjevic,
PRL 112, 042302 (2014)

- **Similar suppression of D mesons and light hadrons at high p_T**
  - Mass ordering is not observed

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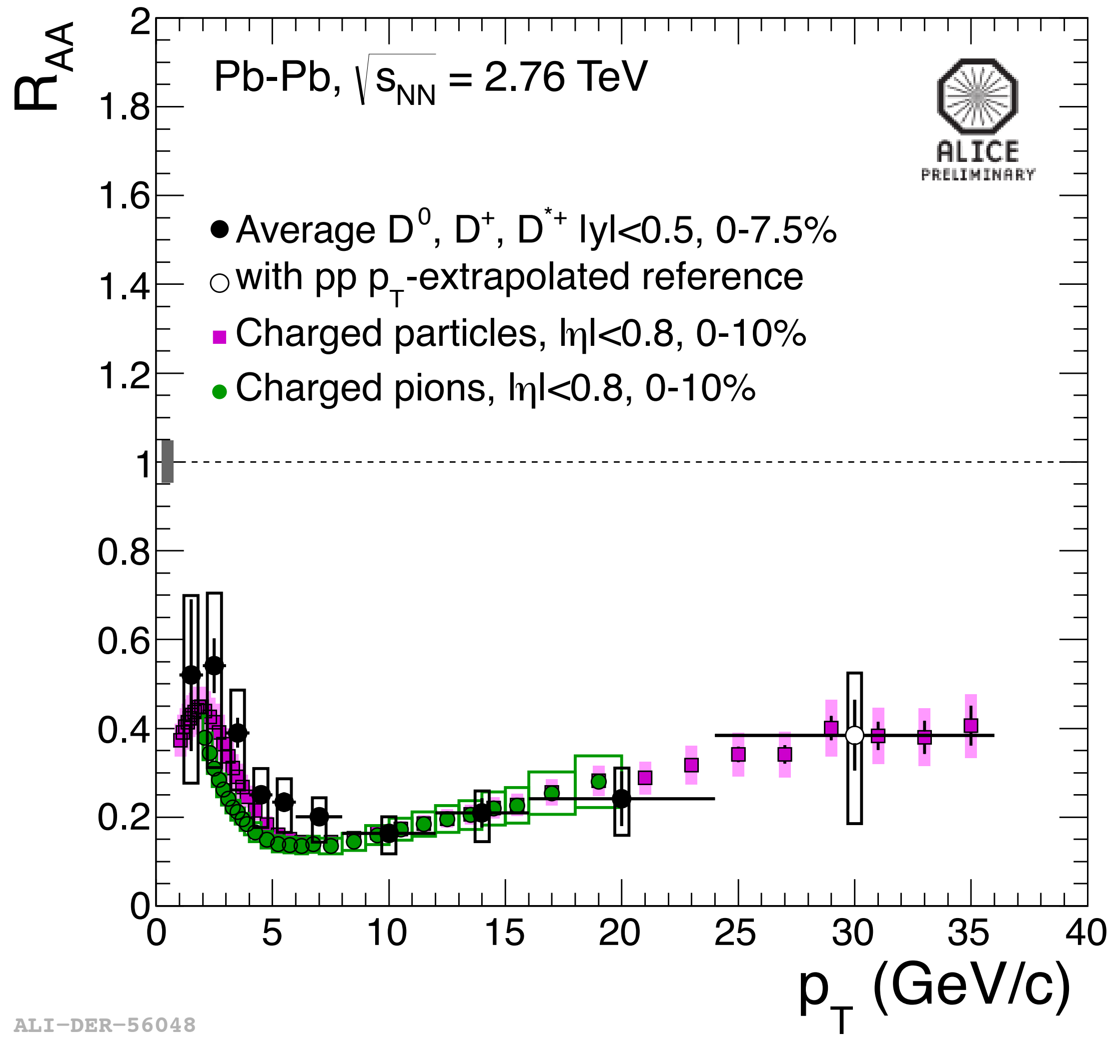

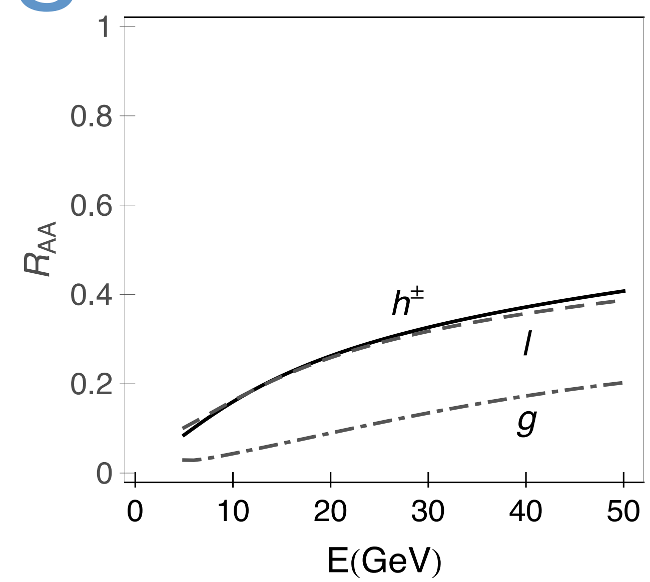

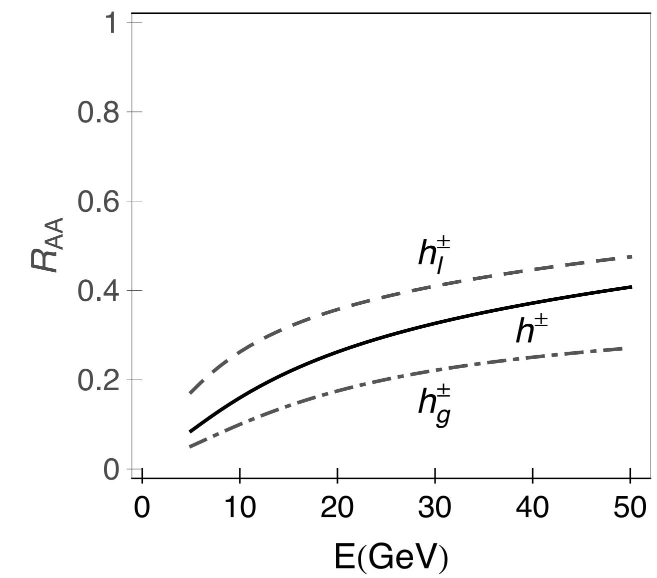

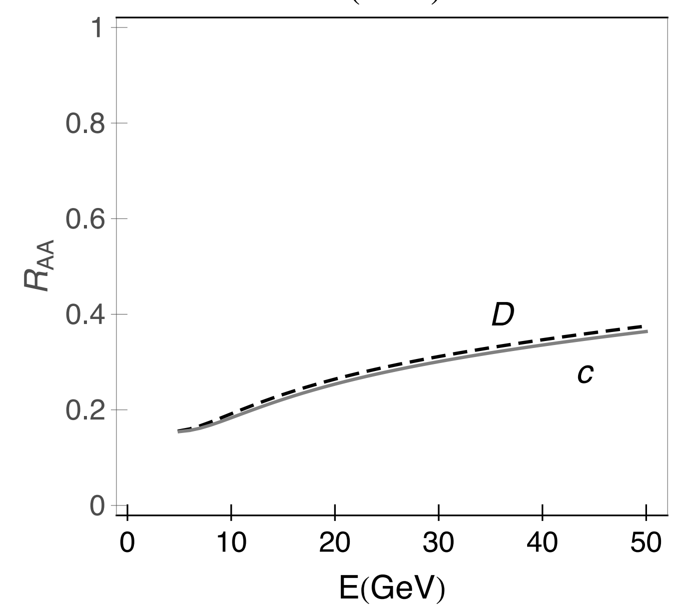

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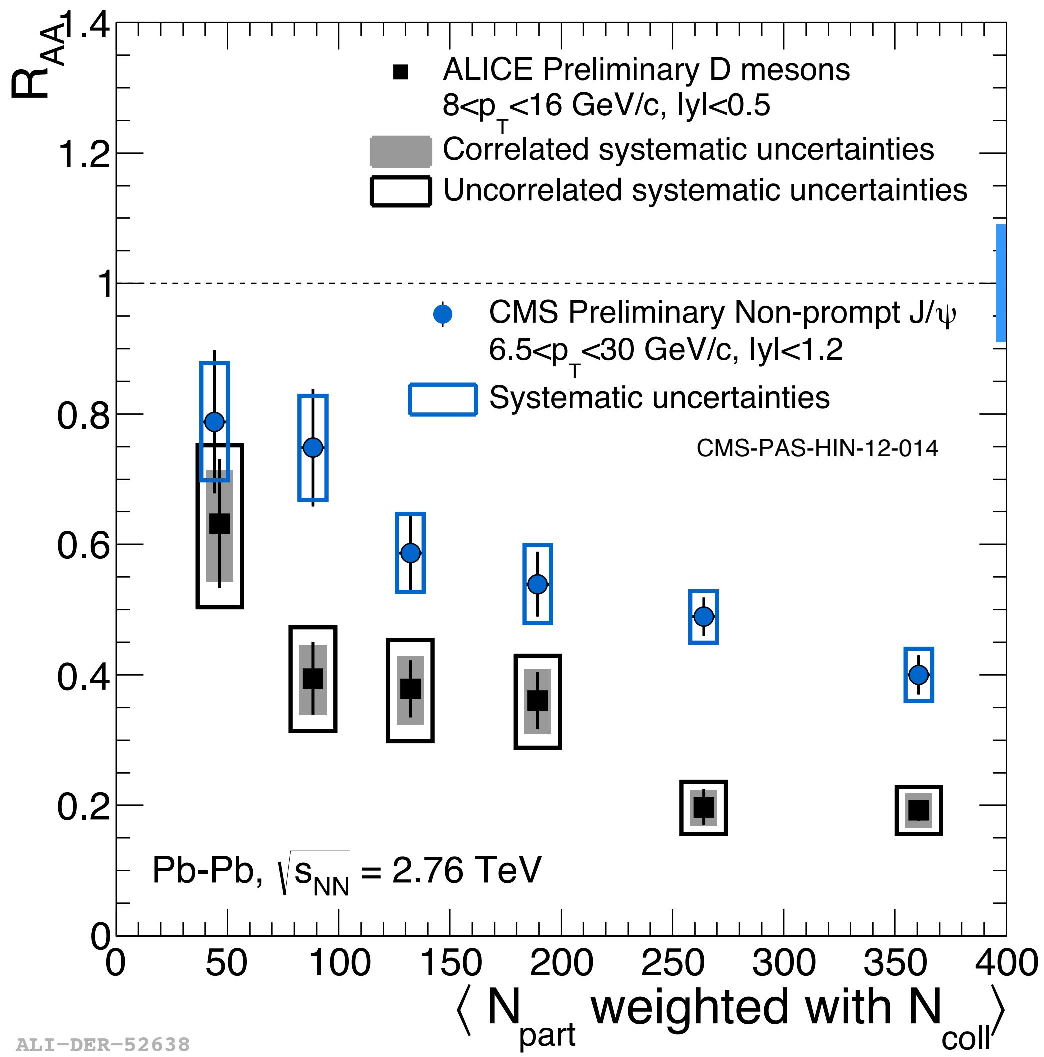
- **Similar suppression of D mesons and light hadrons at high p_T**
  - Mass ordering is not observed
- **Solution: we compare hadron p_T and not parton p_T**
  - fragmentation functions differ for light and heavy partons
  - probe different parton p_T

Charm vs. Beauty



CMS PAS HIN-12-014

- CMS observes suppression of non-prompt J/ψ from b hadron decays
- Matching p_T intervals to probe similar D and B p_T ranges
  - J/ψ p_T ~ 3 GeV lower than B p_T
- **Observe mass ordering of suppression in central Pb–Pb collisions**
  - could be fragmentation but mass dependence reproduced in models

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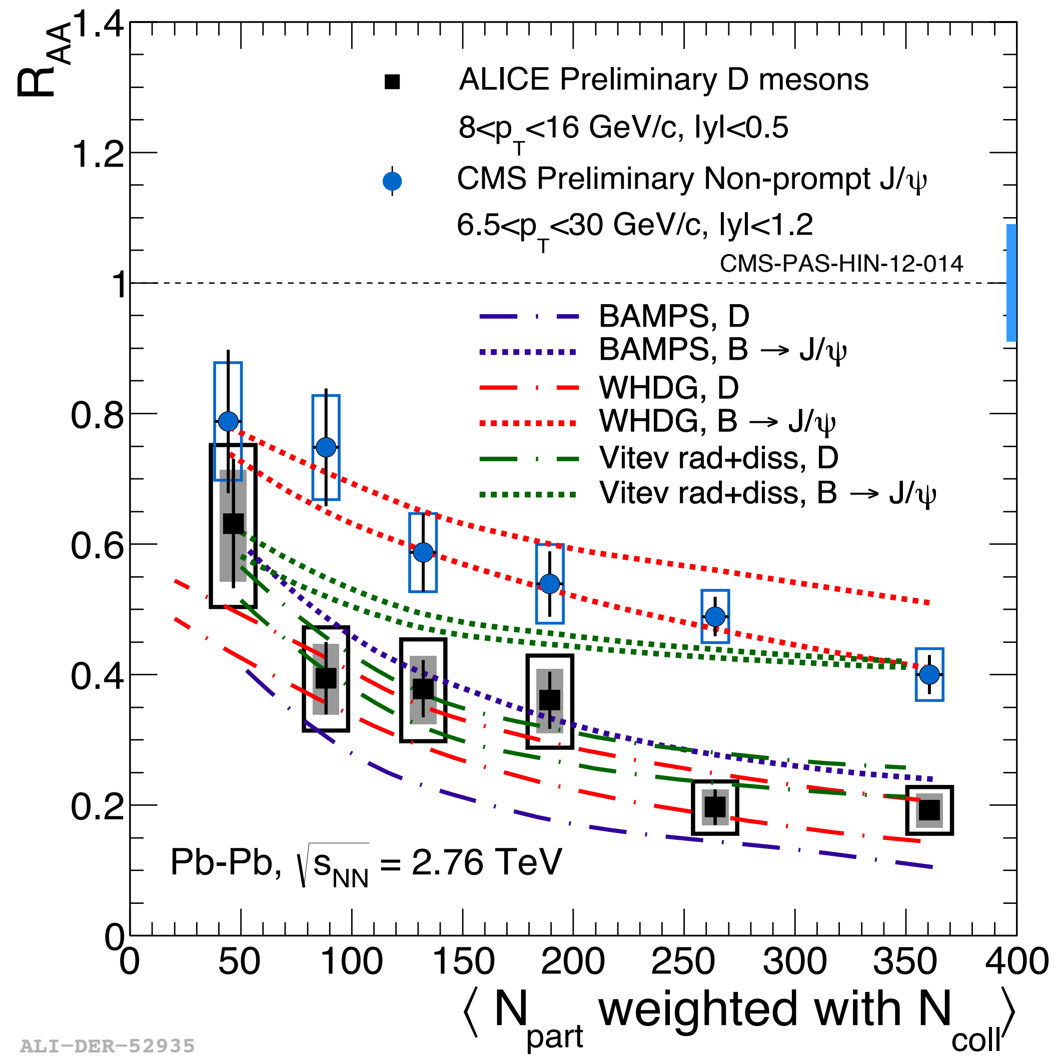

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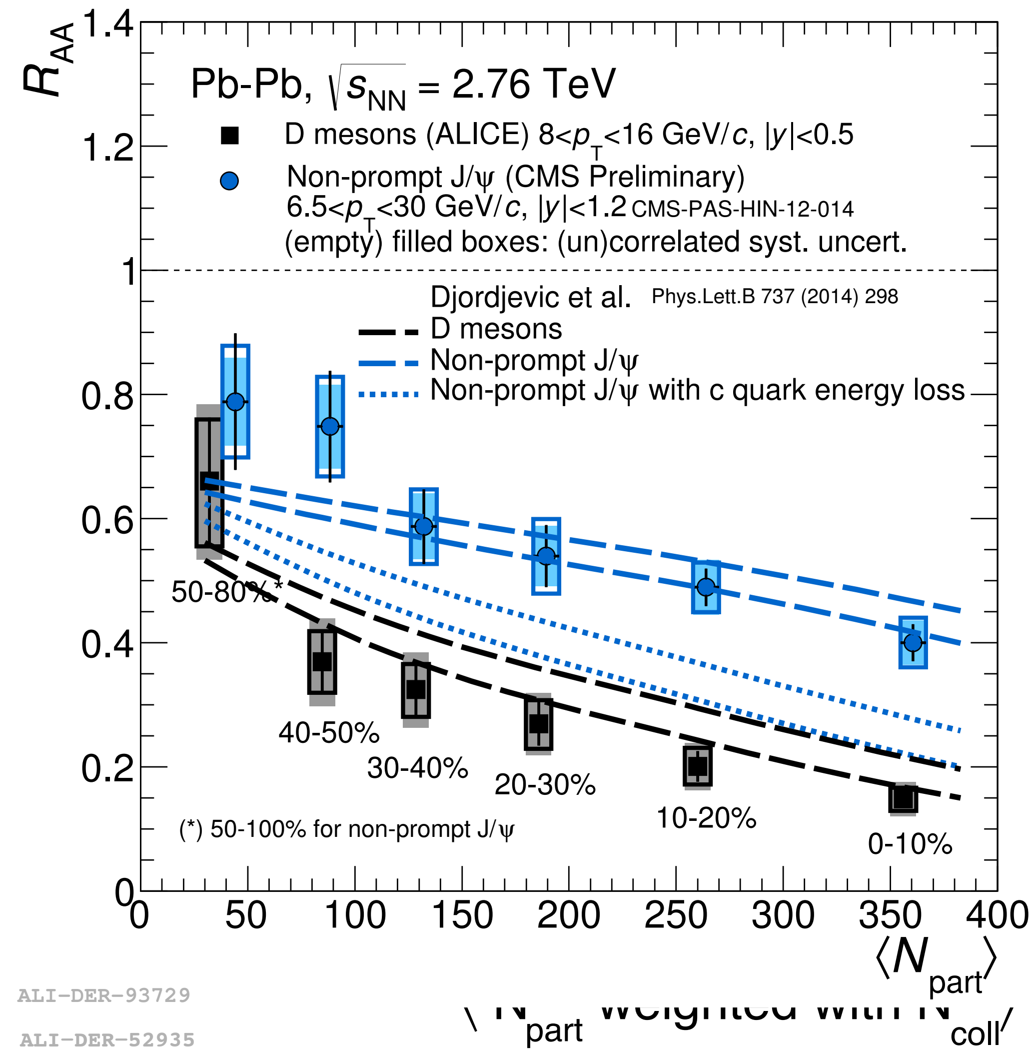

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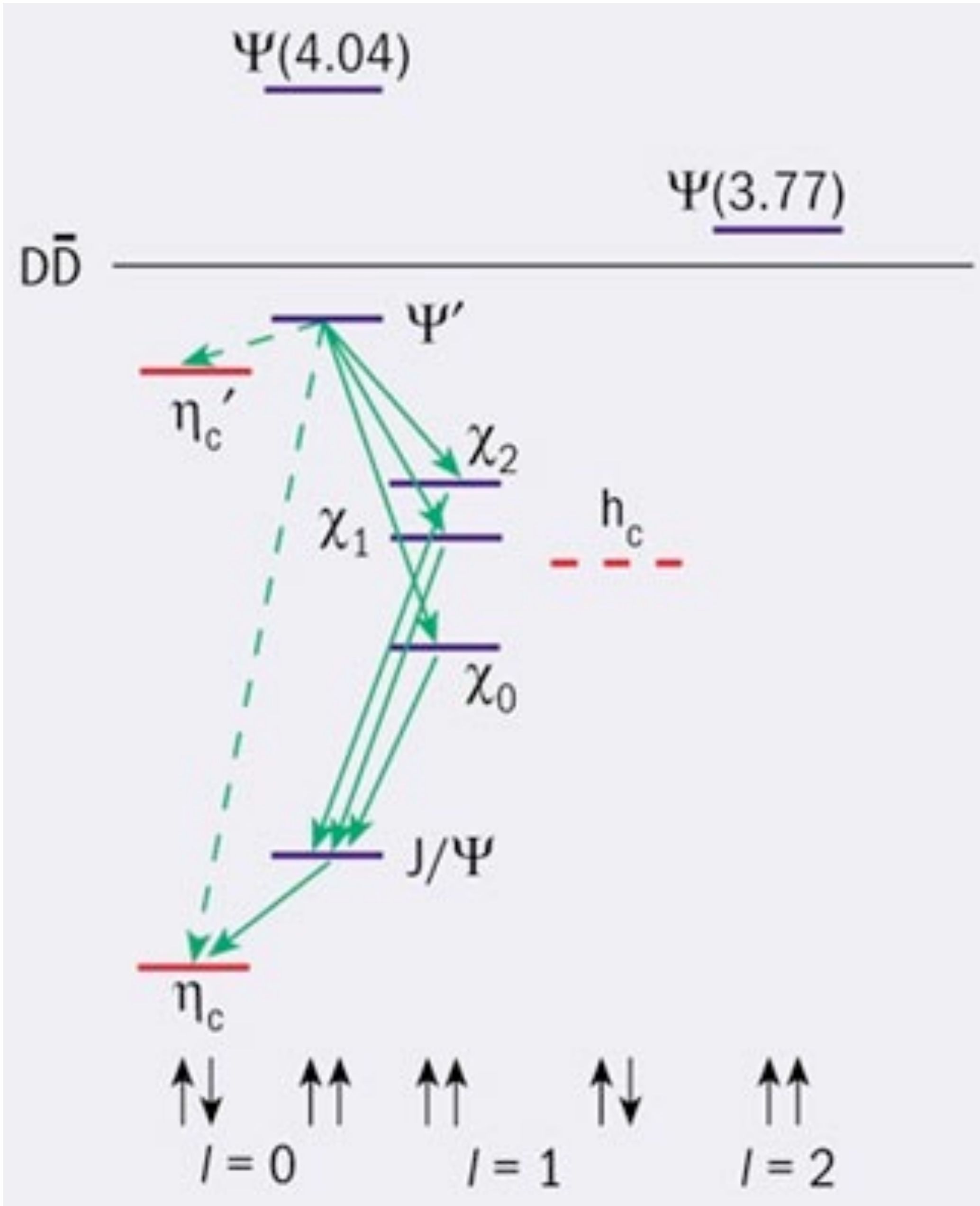
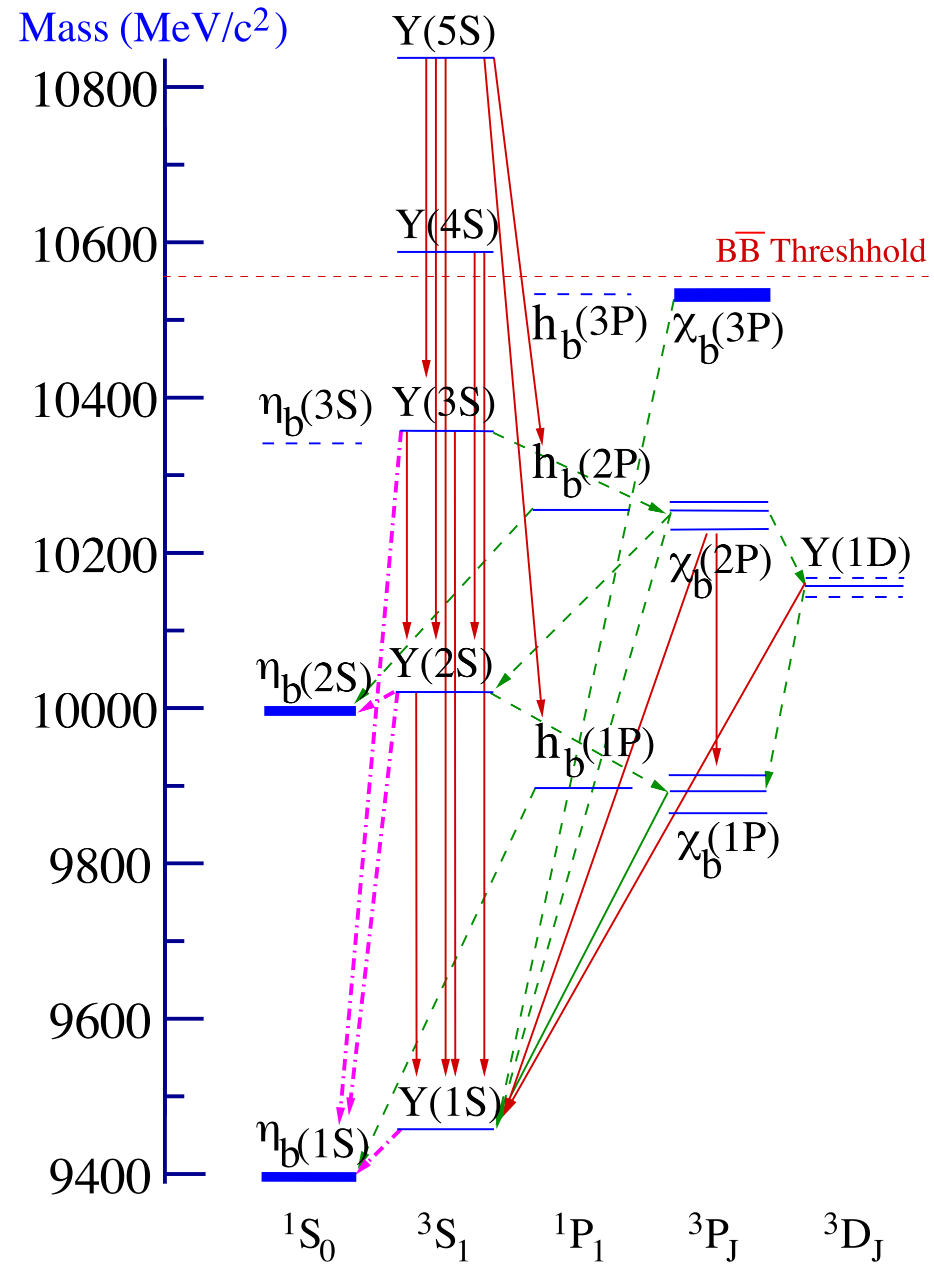
Quarkonia

Quarkonia





- Charmonium: bound states of charm anti-charm pairs
- Bottomonium: bound states of bottom anti-bottom pairs
- Vector S states can decay into a lepton pair:
  - e^+e^- or $\mu^+\mu^-$

Quarkonia

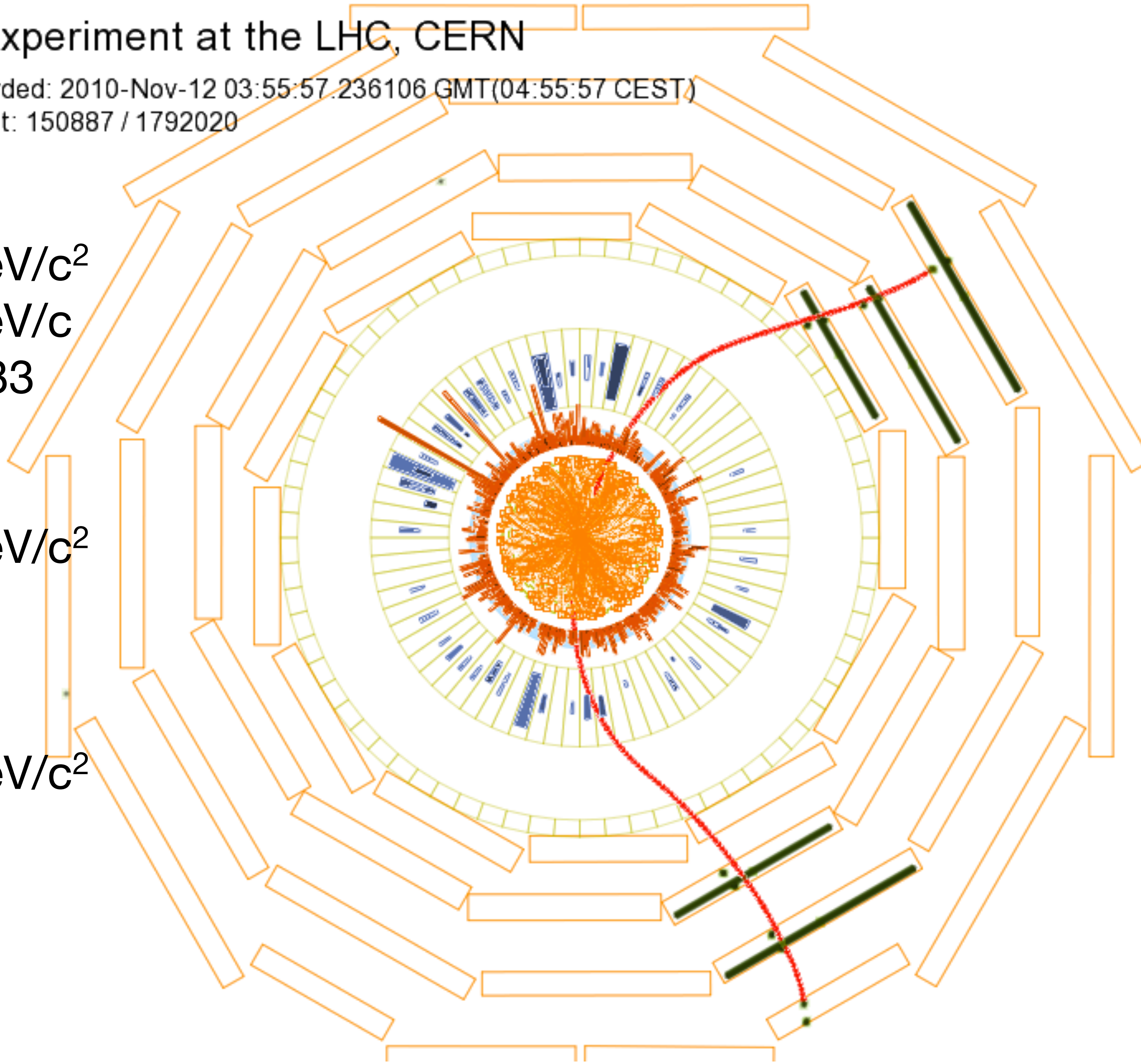
- Unusual hadrons
  - heavy: $m_c \simeq 1.2$–1.4 GeV, $m_b \simeq 4.6$–4.9 GeV
  - stable: $m_{cc} < 2\ M_D$ and $m_{bb} < 2\ M_B$ ($E_{binding} > \Lambda_{QCD}$~0.2 GeV)

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)	Υ (1S)	χ_b (1P)	Υ' (2S)	χ'_b (2P)	Υ'' (3S)
m (GeV/c^2)	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
r_0 (fm)	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

- Compared to usual hadrons
  - made of light quark
  - loosely bound: $m_\rho > 2\ m_\pi$, $m_\phi > 2\ m_K$
  - hadronic size: $1/\Lambda_{QCD}$ ~ 1 fm, independent of mass
  - relative production rates roughly energy independent, described well by statistical hadronization

- **In a QGP with T~300 MeV: quarkonia cannot be produced thermally**

Υ candidate in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



$\mu^+\mu^-$ pair:

mass: 9.46 GeV/c^2

p_T: 0.06 GeV/c

rapidity: –0.33

μ^+:

p_T = 4.74 GeV/c^2

η = –0.39

μ^-:

p_T = 4.70 GeV/c^2

η = –0.28

J/ψ as the Golden Probe of the QGP

- Presence of QGP leads to Debye screening of colour charges
- Debye radius increases with temperature
- When binding radius length exceeds Debye radius:
  - Screening: Melting of bound state

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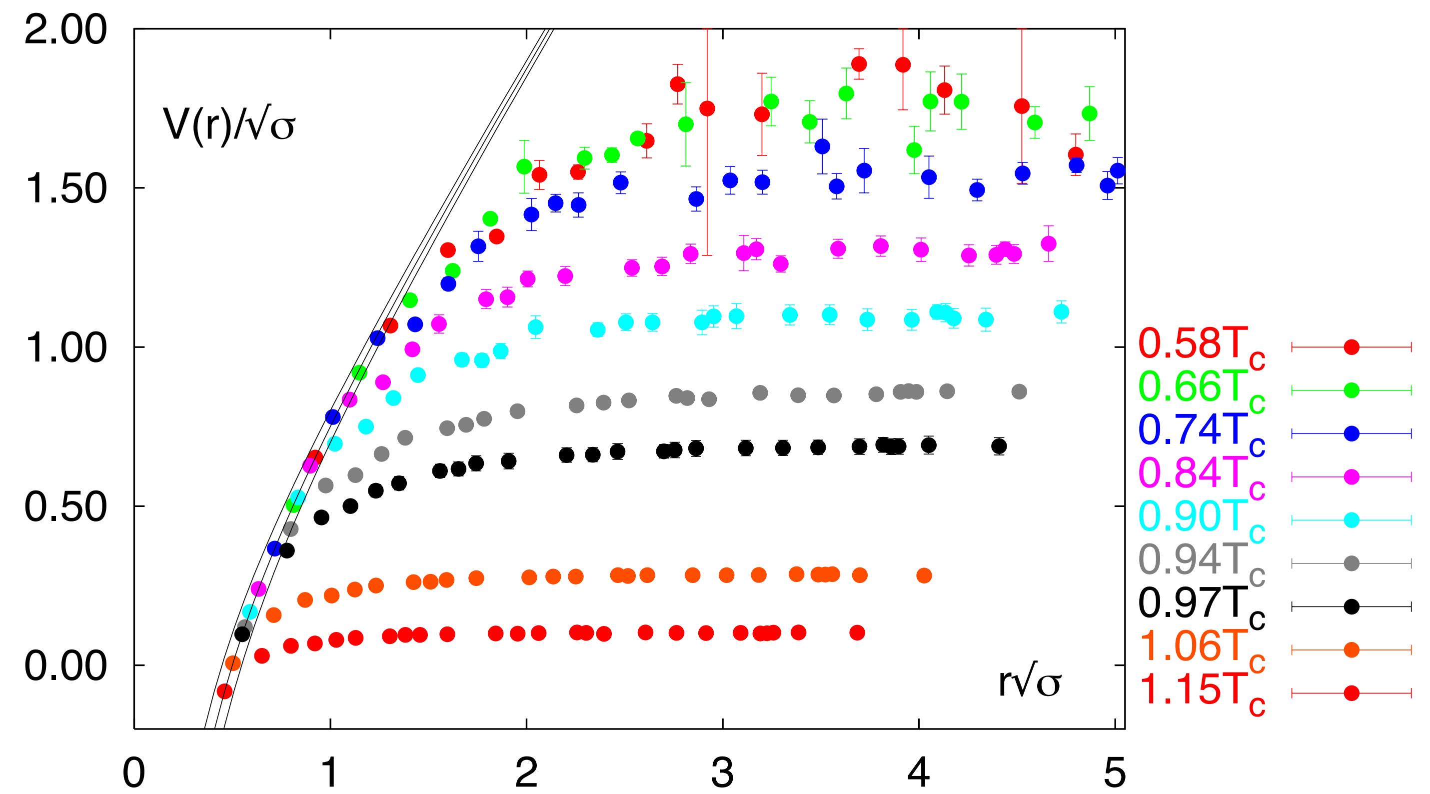

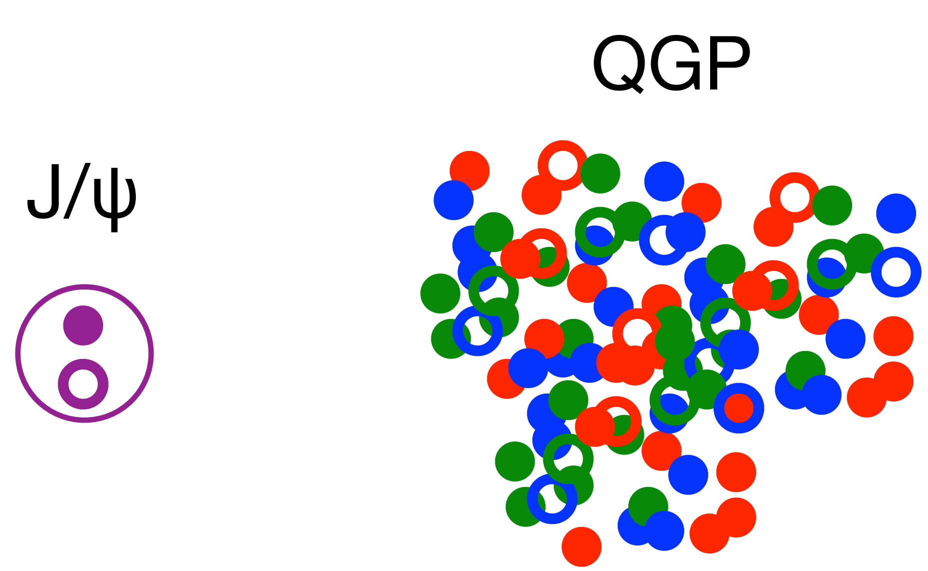

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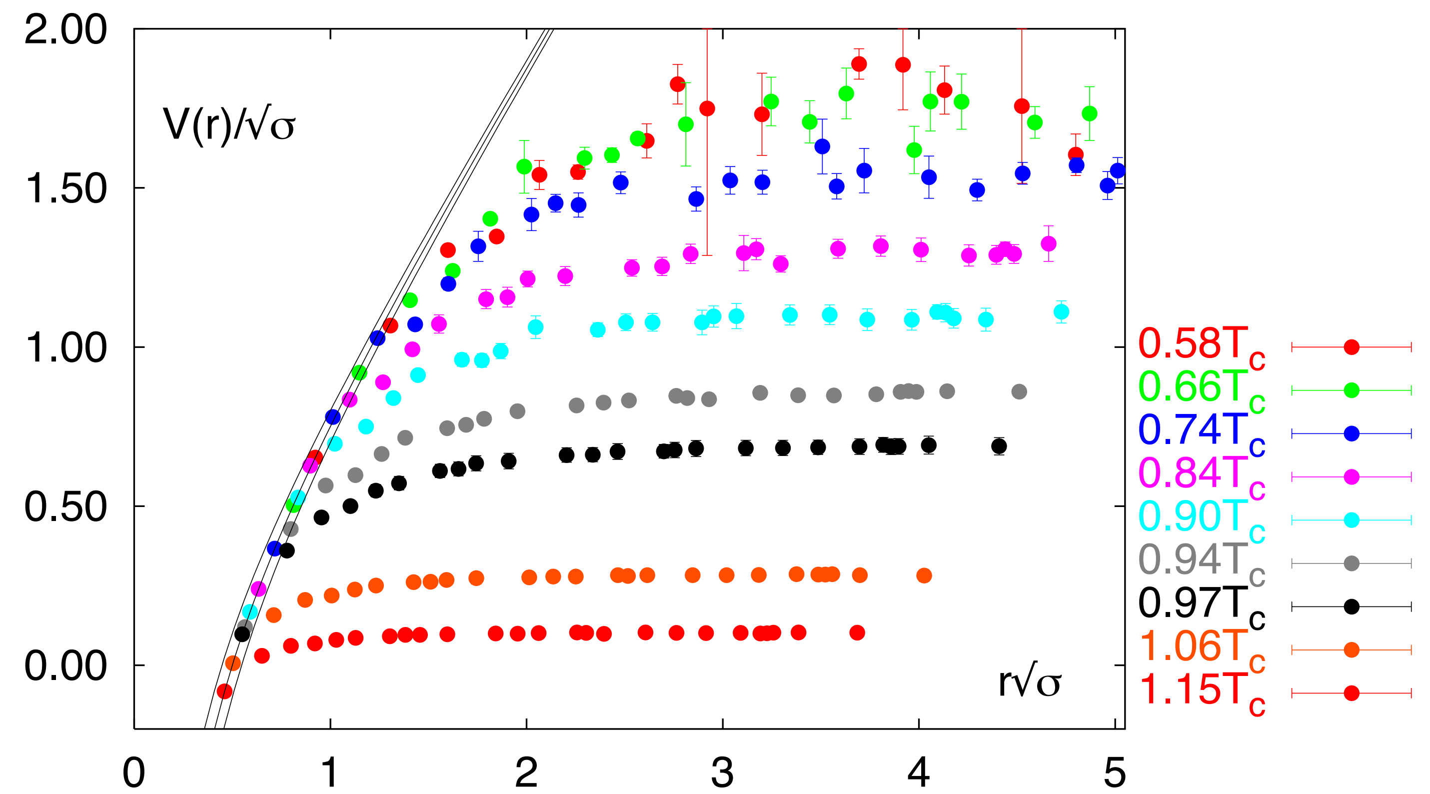

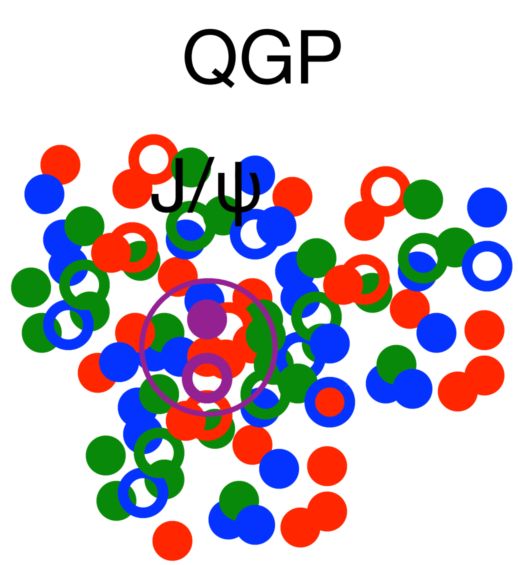

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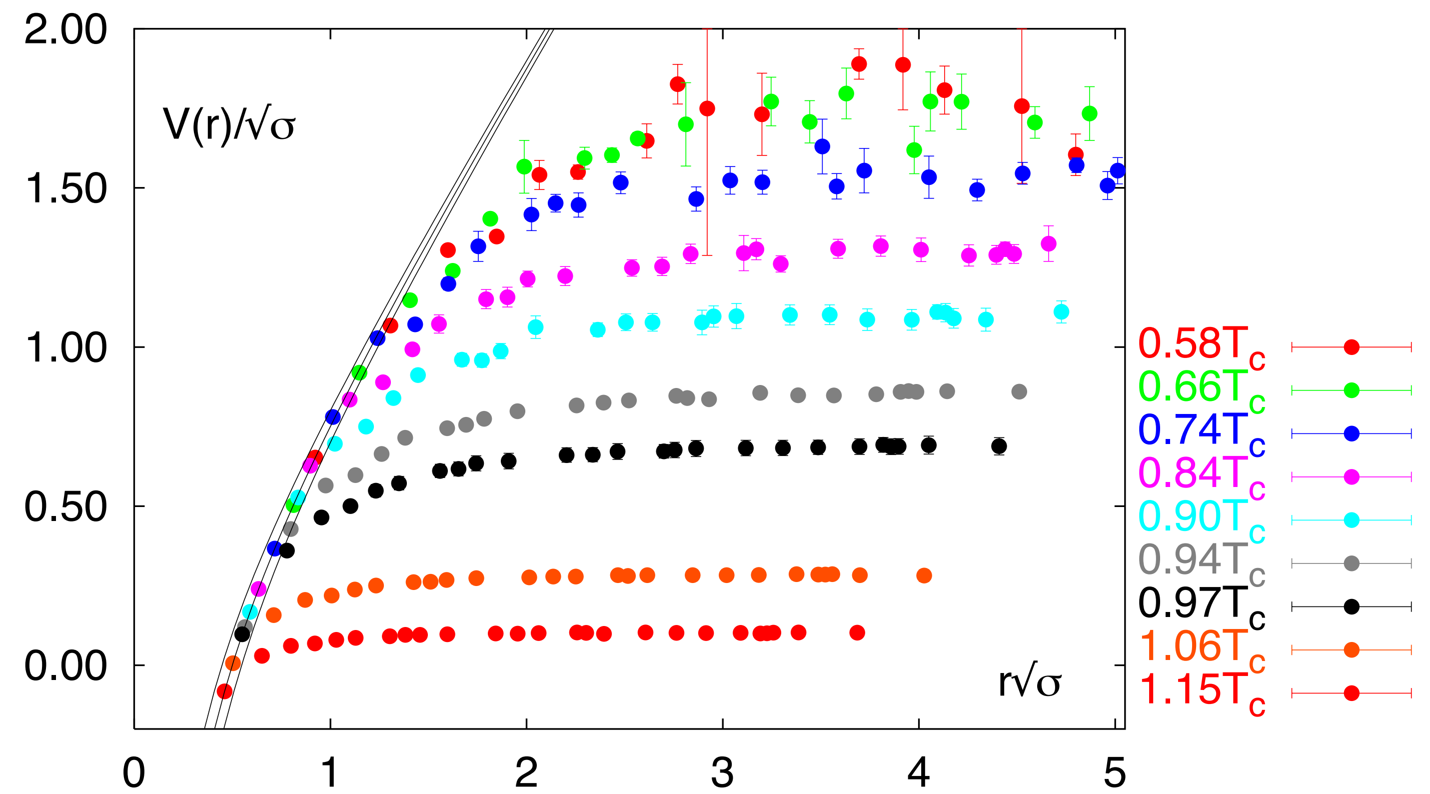

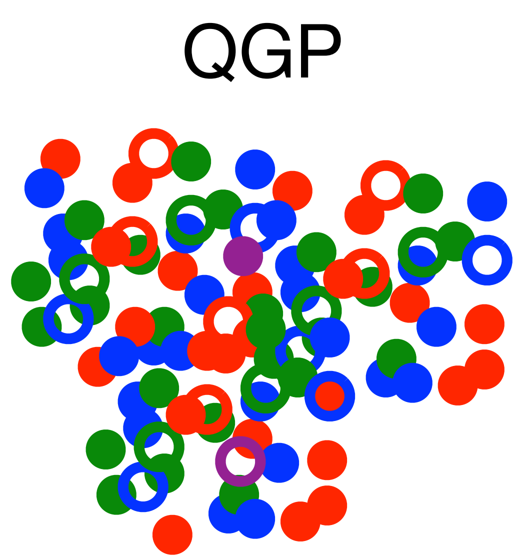

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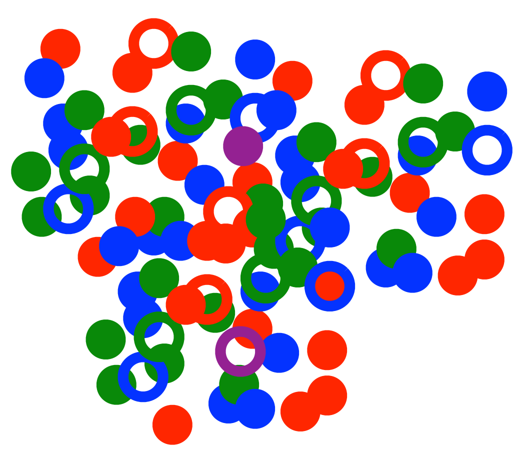
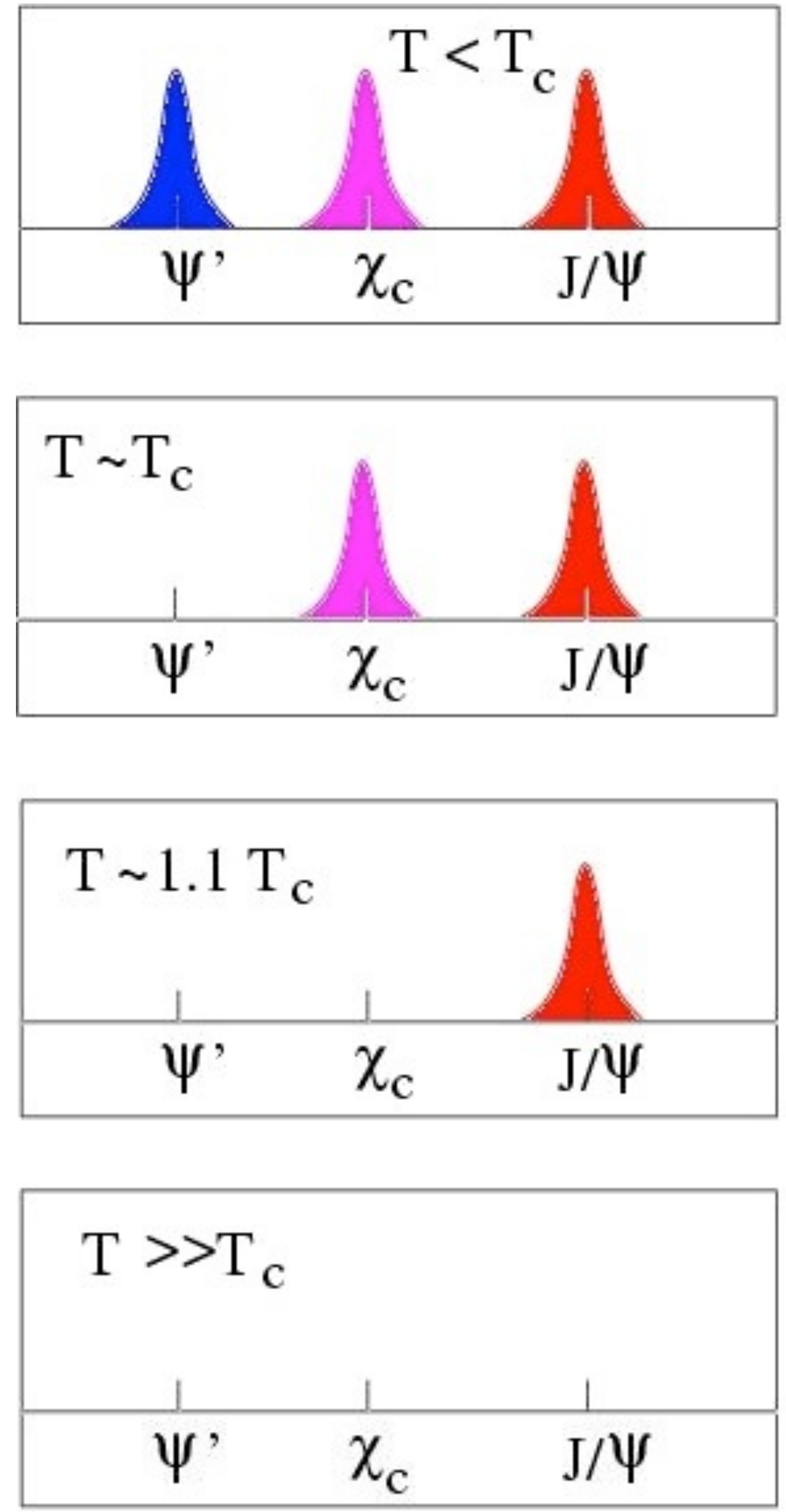
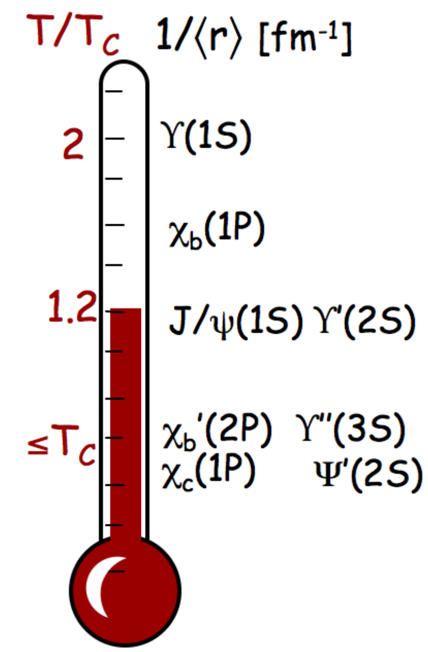
QGP



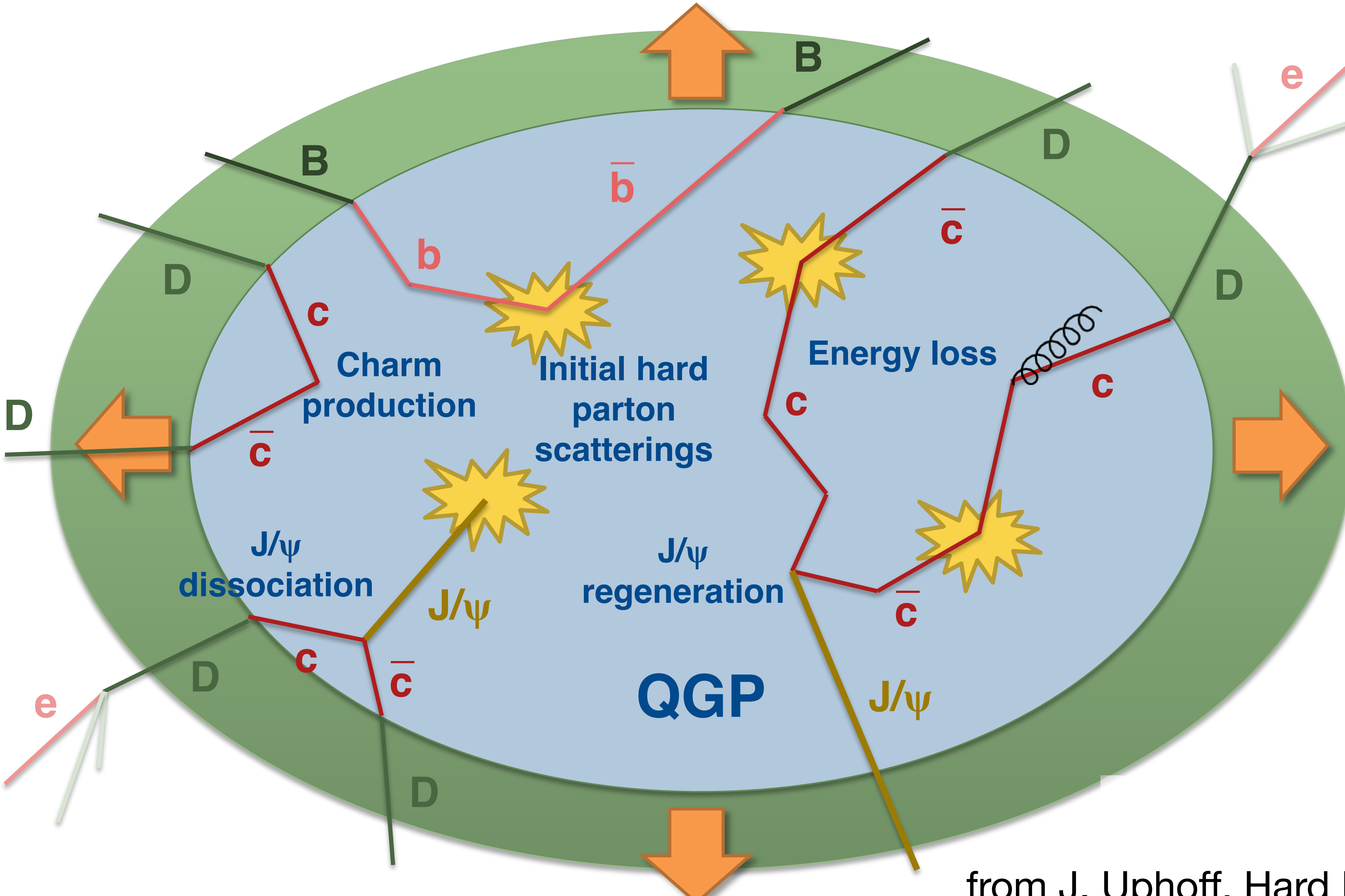




Dissociation vs Regeneration

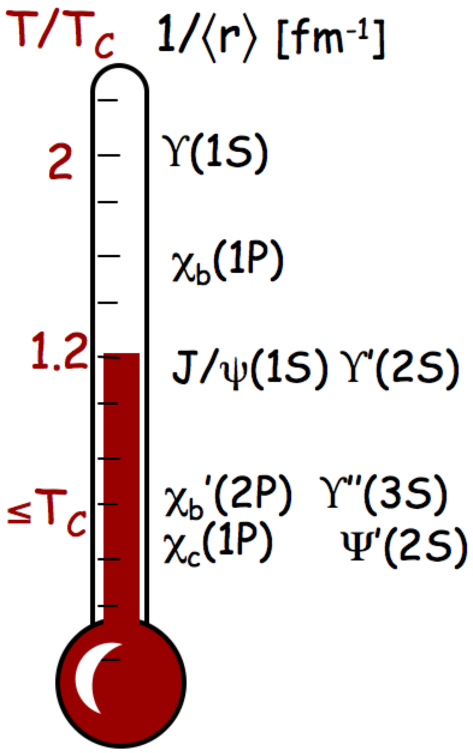
Central Pb–Pb at the LHC: 100 $c\bar{c}$ pairs per collision

(compare to $b\bar{b}$: 10 pairs)



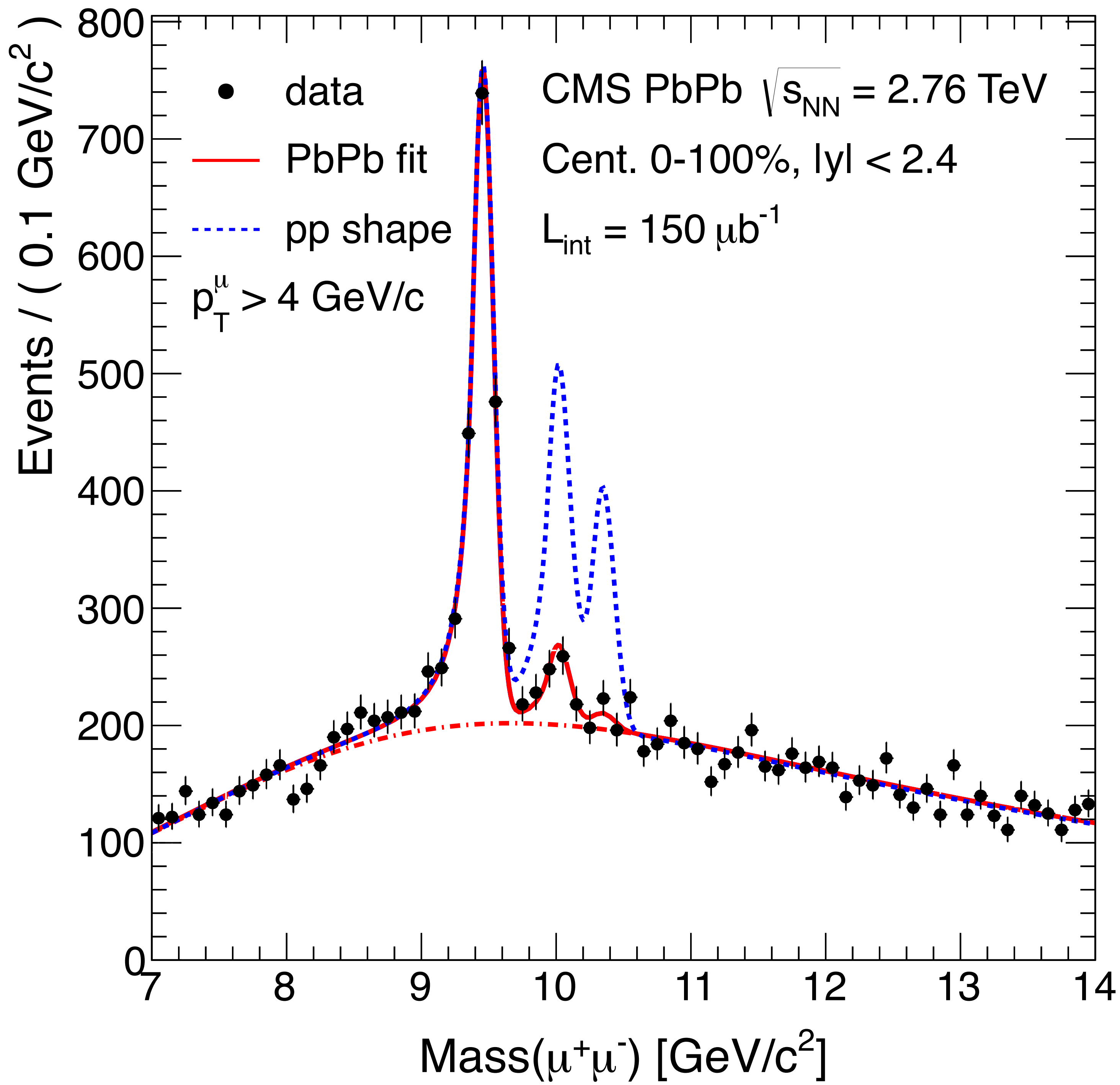
from J. Uphoff, Hard Probes 2013

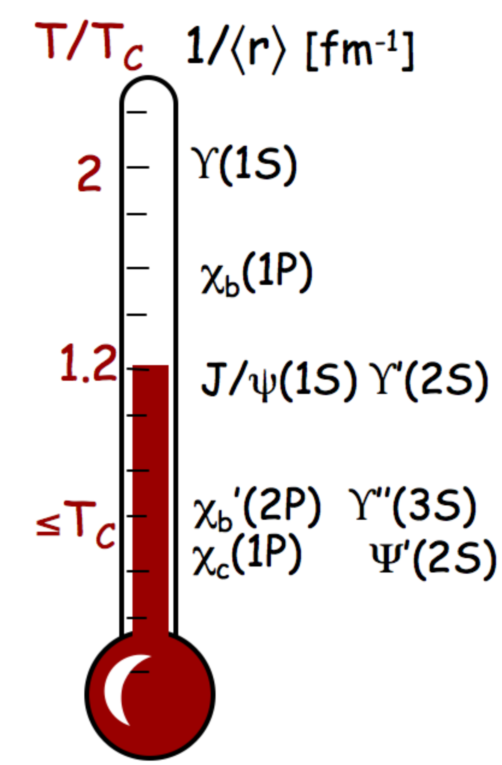
Bottomonia as Thermometer



- **Sequential suppression in order of binding energy**
- Smoking gun for screening?

Bottomonia as Thermometer





- **Sequential suppression in order of binding energy**
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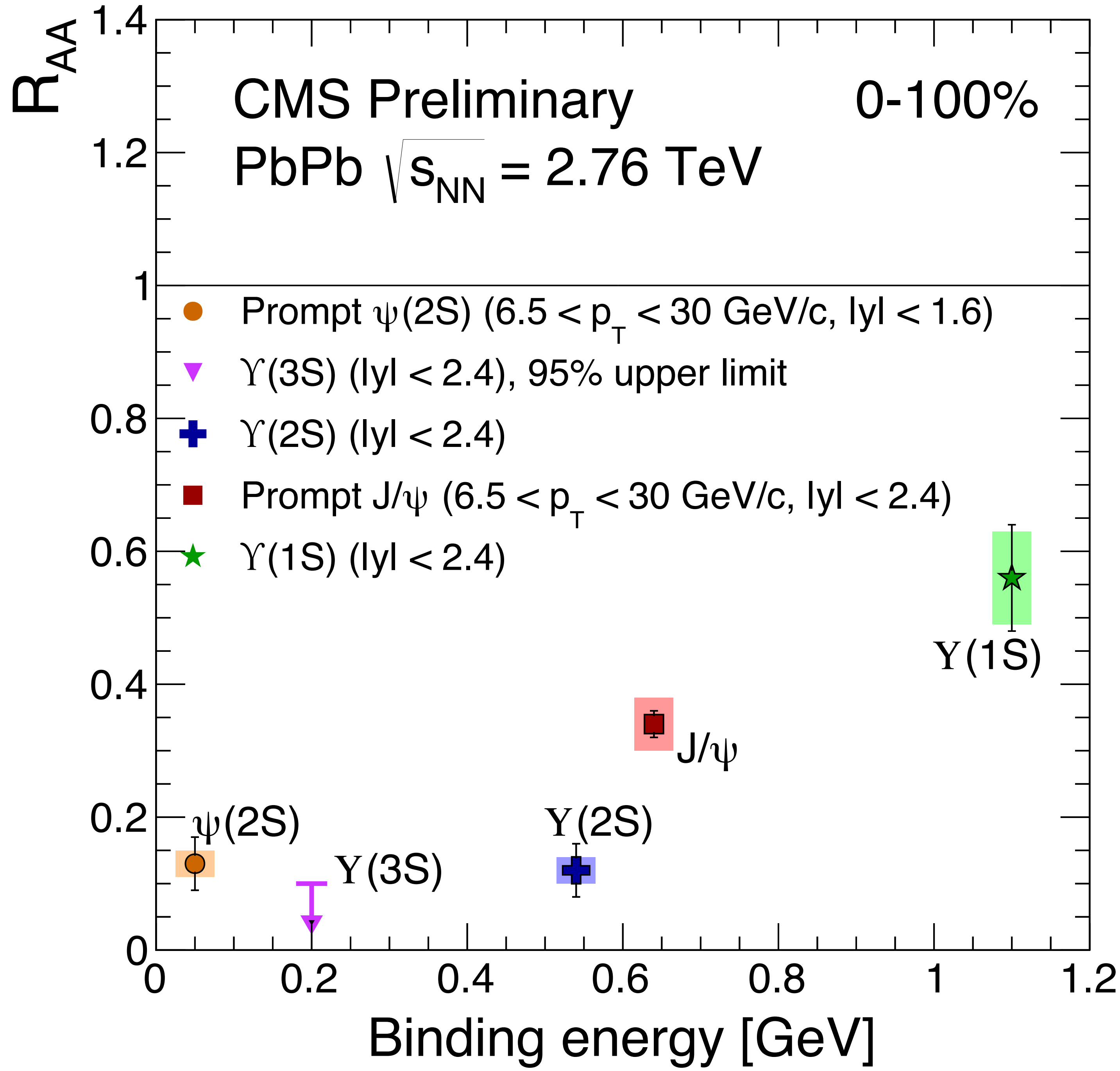
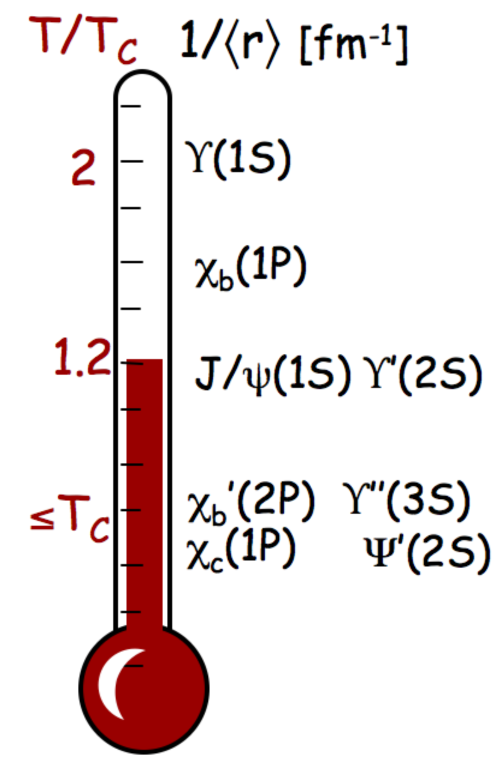
Quarkonium Thermometer

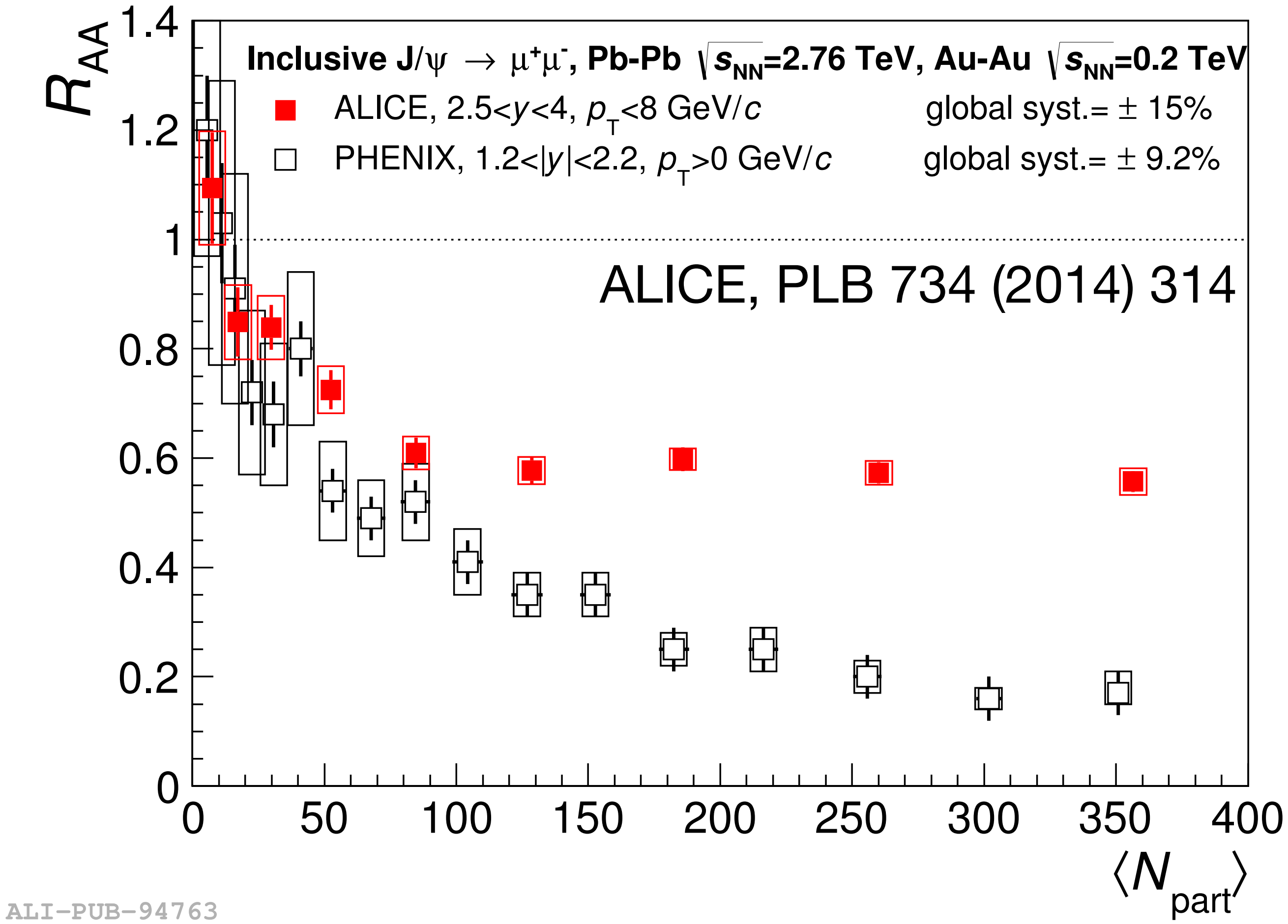




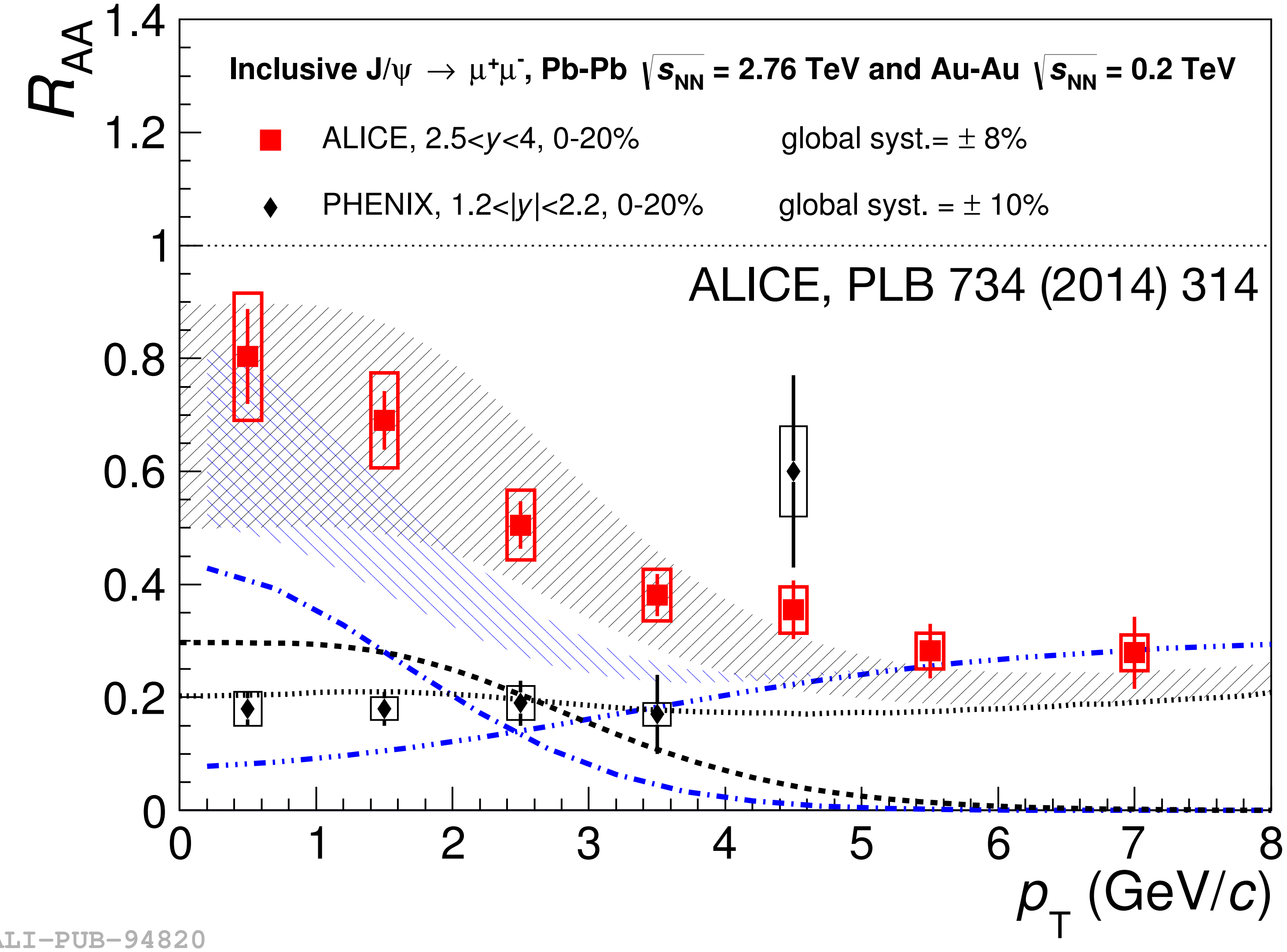
- **Sequential suppression in order of binding energy**
- Smoking gun for screening?
- Caveat: charmonia measured at high p_T

Low p_T J/ψ

- **Sequential dissociation:**
  - higher energy density
    → stronger suppression
- **Regeneration:**
  - larger charm cross section
    → more regeneration
    → less suppression
- Less suppression at LHC than at RHIC (×10 increase in energy)
  - RHIC: $\sqrt{s_{NN}}$ = 200 GeV
  - LHC: $\sqrt{s_{NN}}$ = 2.76 TeV
- **RHIC: dominated by dissociation**
- **LHC: significant regeneration**



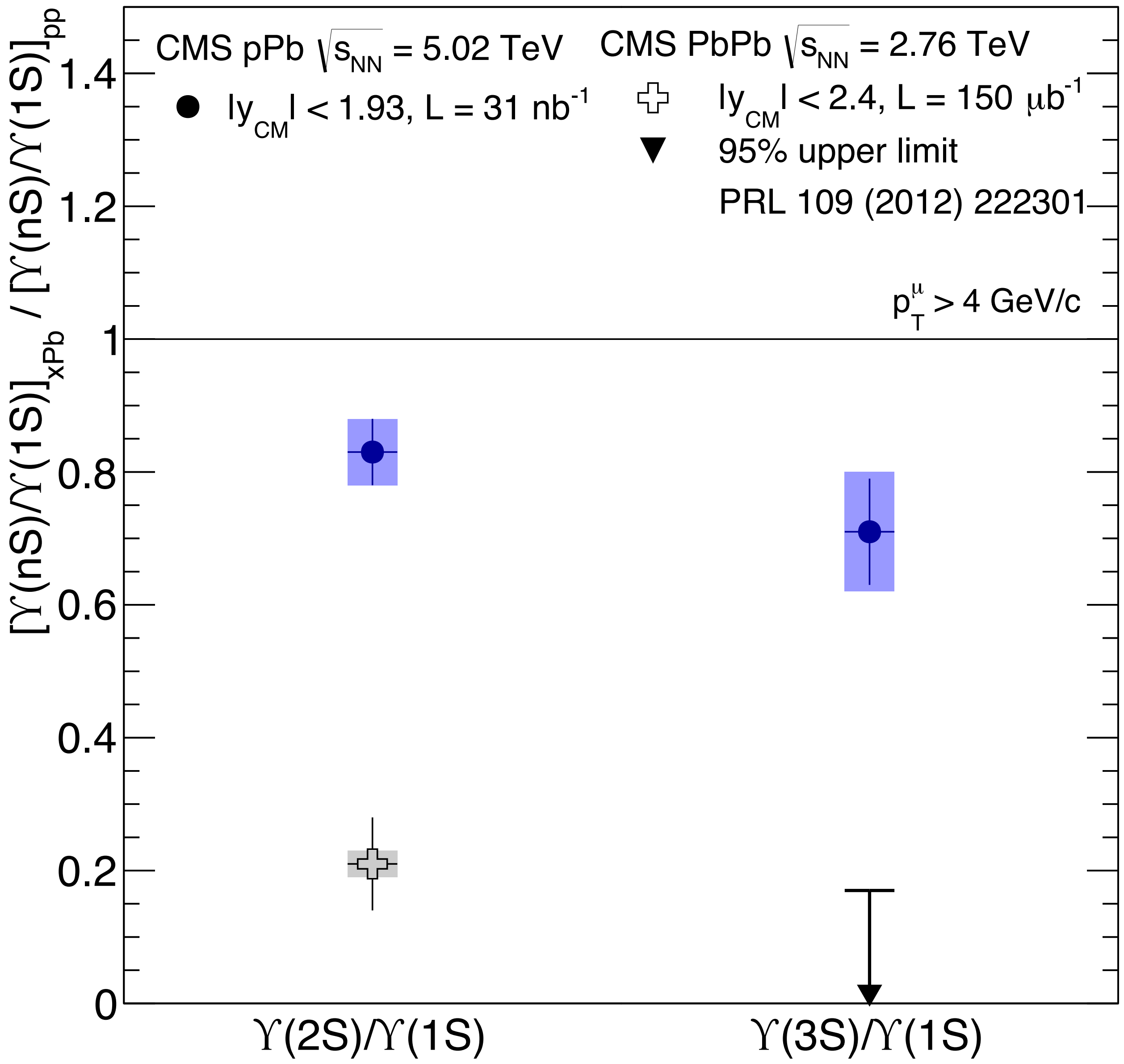
Low pT J/ψ



- RHIC: suppression almost independent of p_T
- LHC: much less suppression at low p_T
- Regeneration component quasi thermal, i.e. dominates low p_T
- **Regeneration picture confirmed in p_T dependence**

Complications for Bottomonia

CMS HIN-13-003
JHEP 04 (2014) 103



- **pPb ratio less than pp:**
  - double ratio less than unity (significance <3σ)
  - Different CNM on excited states?
- **pPb ratio larger than in Pb–Pb**
  - suggests additional final effects in Pb–Pb
  - but: model dependent extrapolation from pPb to Pb–Pb
- On top:
  multiplicity dependence in pp and pPb

Summary

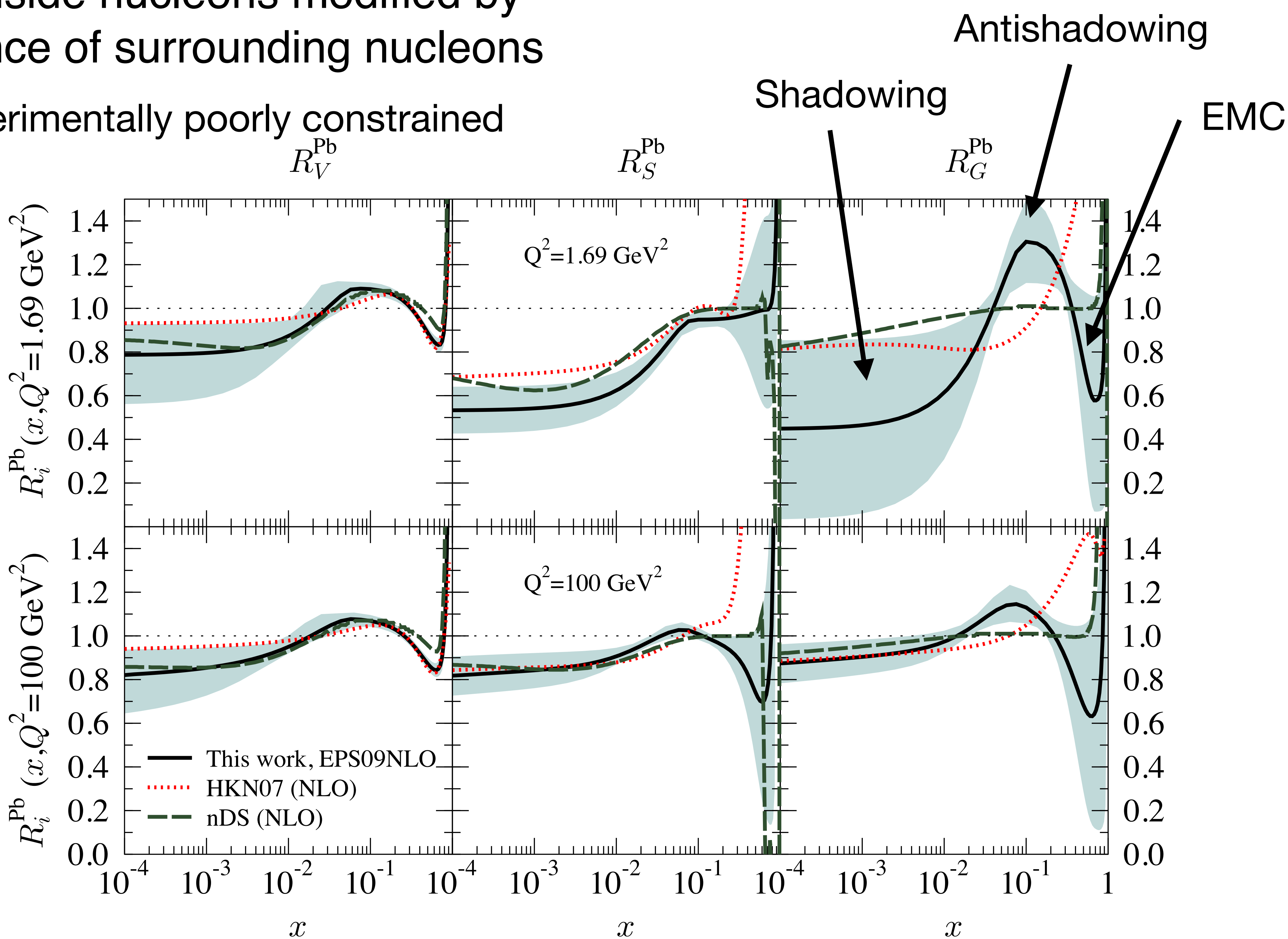
- Electroweak probes confirm binary scaling of hard probes
  - shadowing effects at 10% level
- Jet tomography of the QGP provides new insights about QGP properties
  - no change of jet direction
  - jet energy goes into (isotropic) soft particle production
- Open heavy flavour suppression shows first signs of mass dependence of QCD energy loss
  - complicated by parton dependent fragmentation functions
- Quarkonia: 30 years of "golden signature" but "all that glisters is not gold"
  - Not a simple thermometer
  - Regeneration component requires partonic medium
- Future:
  - γ/Z-jet to avoid surface bias
  - HF correlation studies
  - …

Enjoy the Conference

Backup

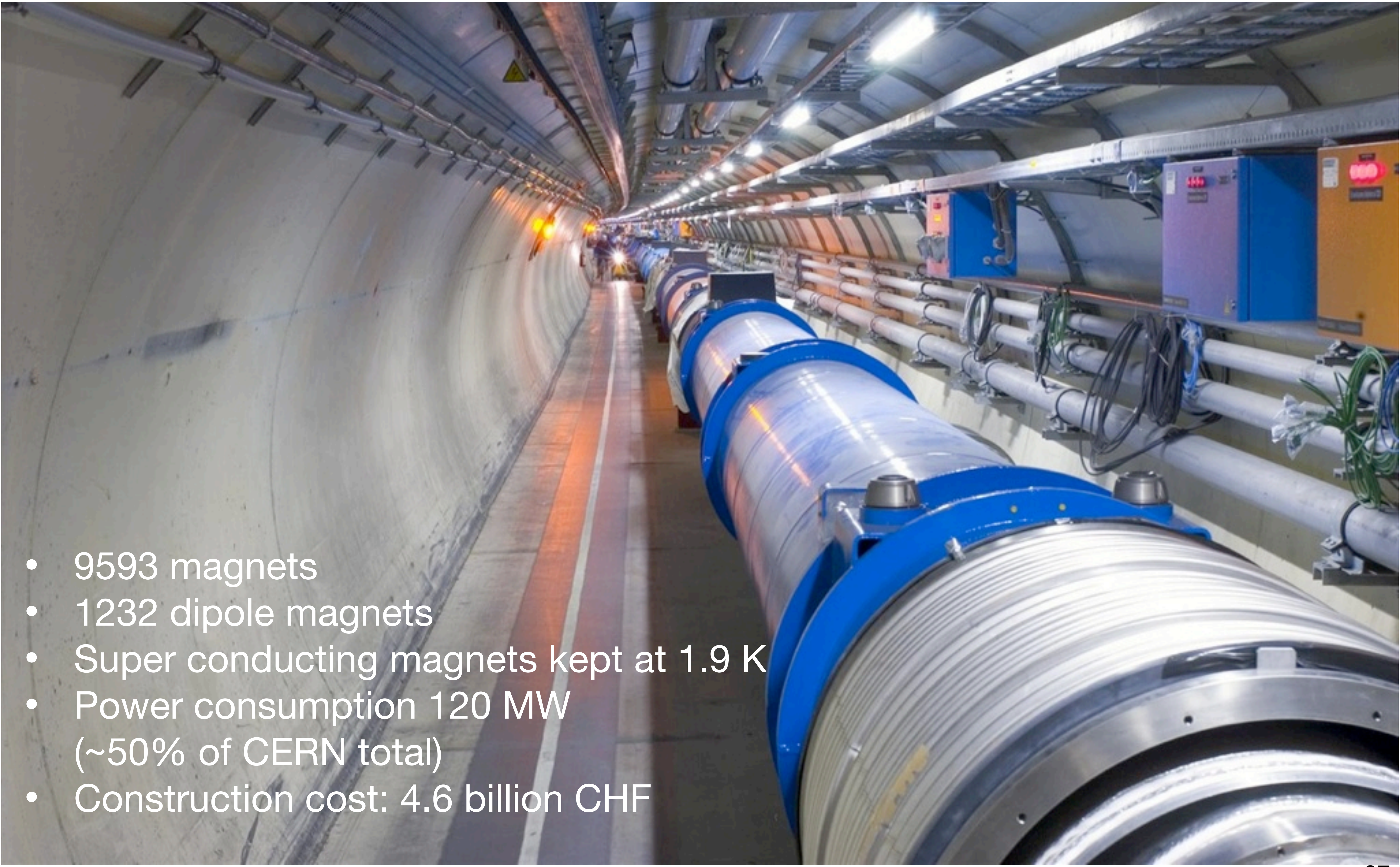
Nuclear PDF

- PDF inside nucleons modified by presence of surrounding nucleons
  - experimentally poorly constrained



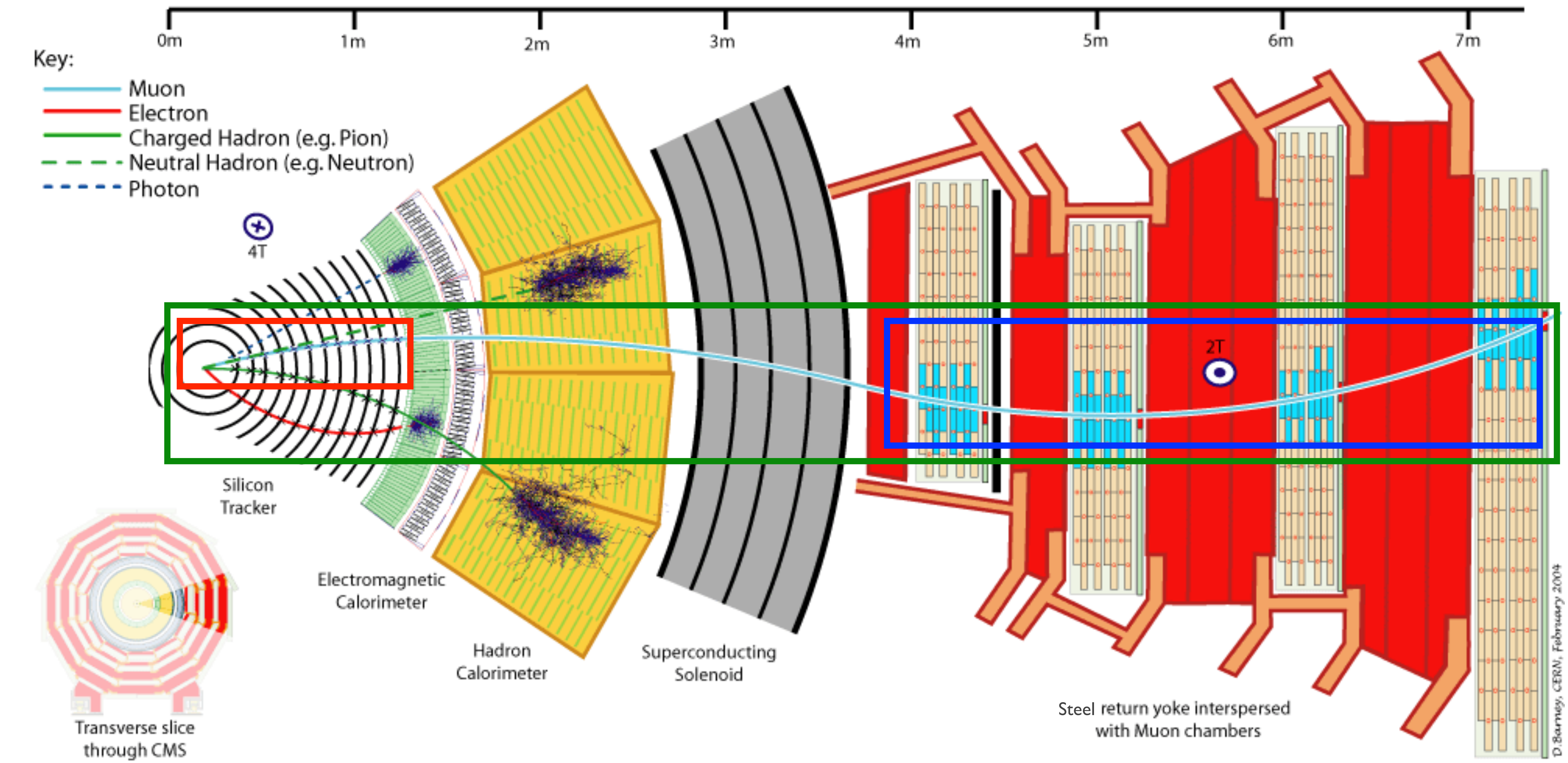
Eskola, Paukkunen, Salgado, JHEP 04 (2009) 065

The Large Hadron Collider



- 9593 magnets
- 1232 dipole magnets
- Super conducting magnets kept at 1.9 K
- Power consumption 120 MW (~50% of CERN total)
- Construction cost: 4.6 billion CHF

Particle Reconstruction in CMS



- Muons reconstructed with information from inner tracker and muon stations
- Inner track reconstruction provides excellent momentum and vertexing information

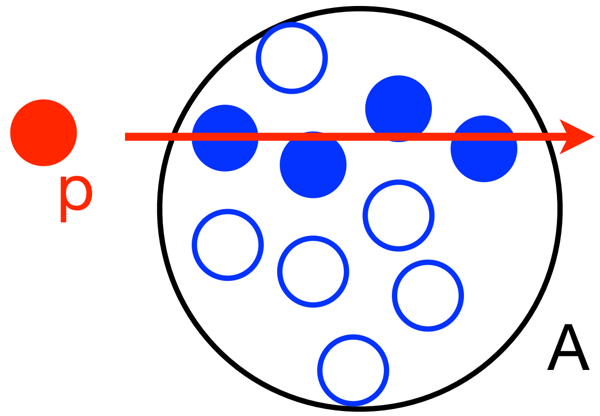
Multiplicity in p+A Collisions

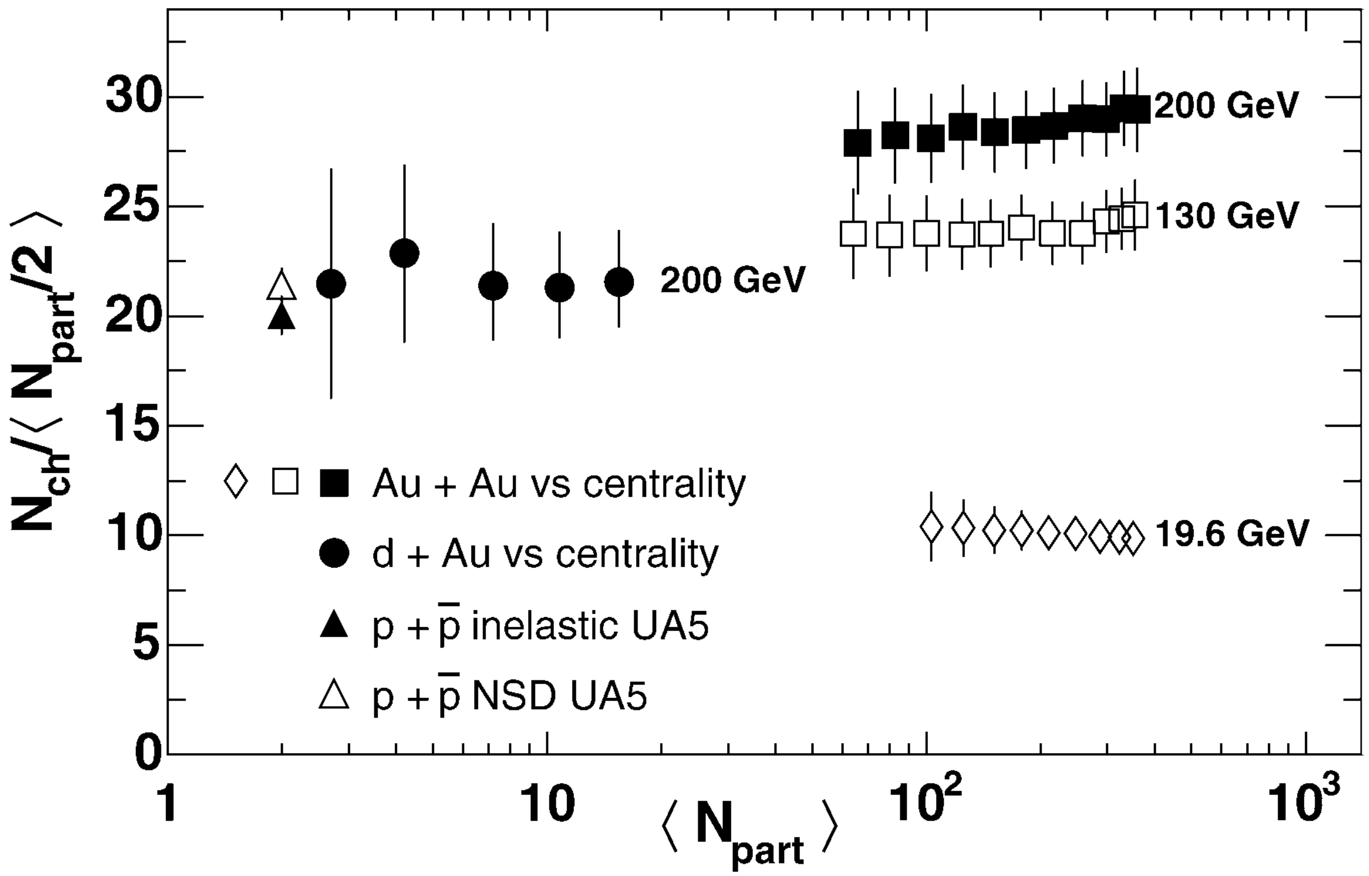
- For pA collisions:
  - $N_{part} = N_{coll} + 1$
- How do particles scale?
  - with N_{coll} or N_{part}
- Observation:
  - Particle production scales with N_{part}

$$\langle N_{ch}^{p+A} \rangle \approx \frac{N_{part}}{2} \langle N_{ch}^{p+p} \rangle$$

(wounded nucleon model)

- However:
step in N_{ch}/N_{part} from pA to A–A!

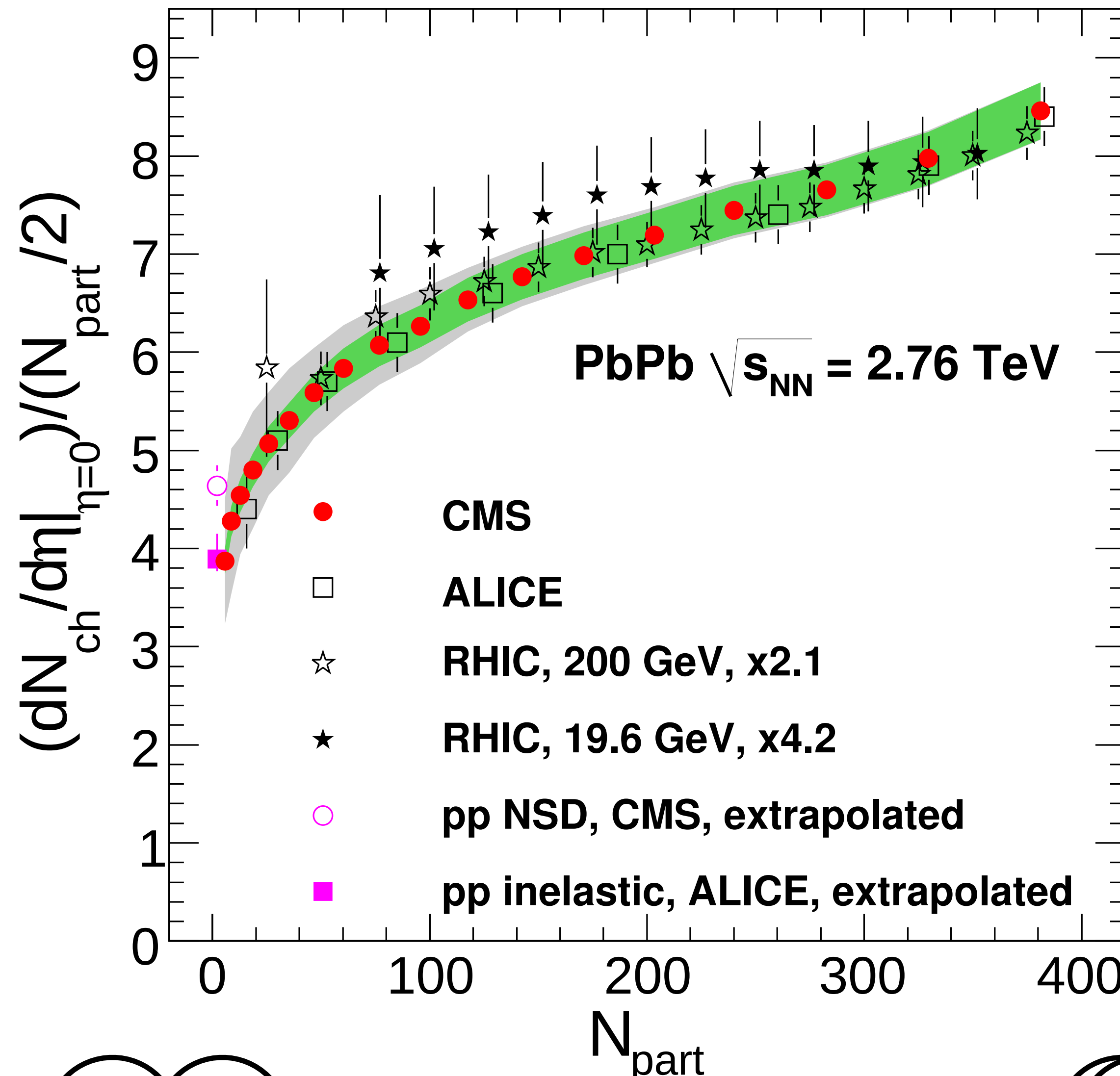




PHOBOS, Nucl. Phys. A 757 (2005) 28

$dN_{ch}/d\eta$ vs. N_{part}

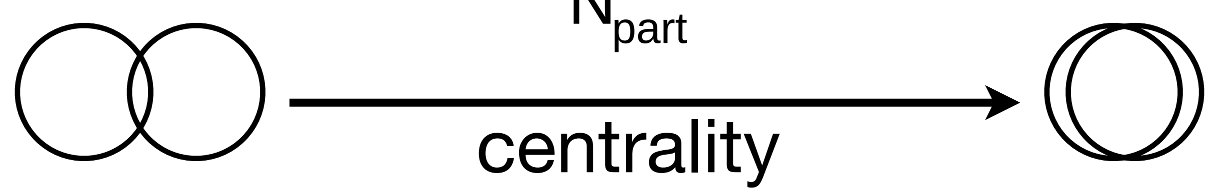
ALICE, PRL 106 (2011) 032301
CMS, JHEP 08 (2011) 141



$$N_{\text{part}}^{\text{max}} = 2A$$

$$(= 416 \text{ for Pb})$$

$$(= 394 \text{ for Au})$$



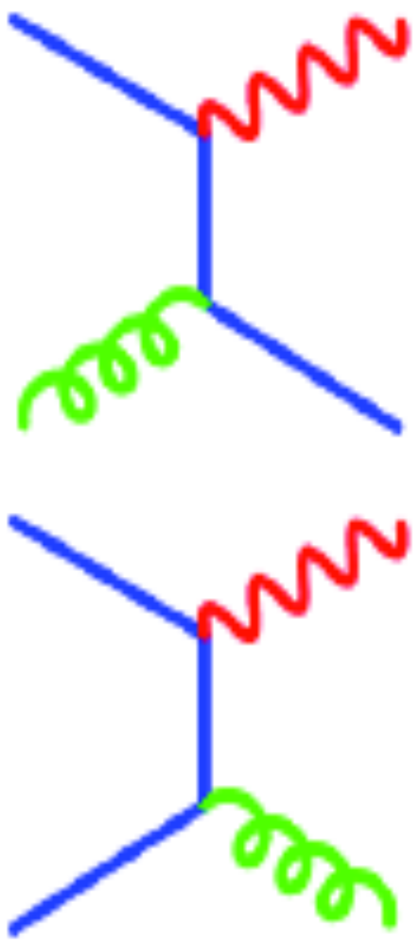
- Relative increase of multiplicity with N_{part} independent of collision energy
  - same at RHIC and LHC spanning 2 orders of magnitude of $\sqrt{s_{NN}}$

Sources of Prompt Photons

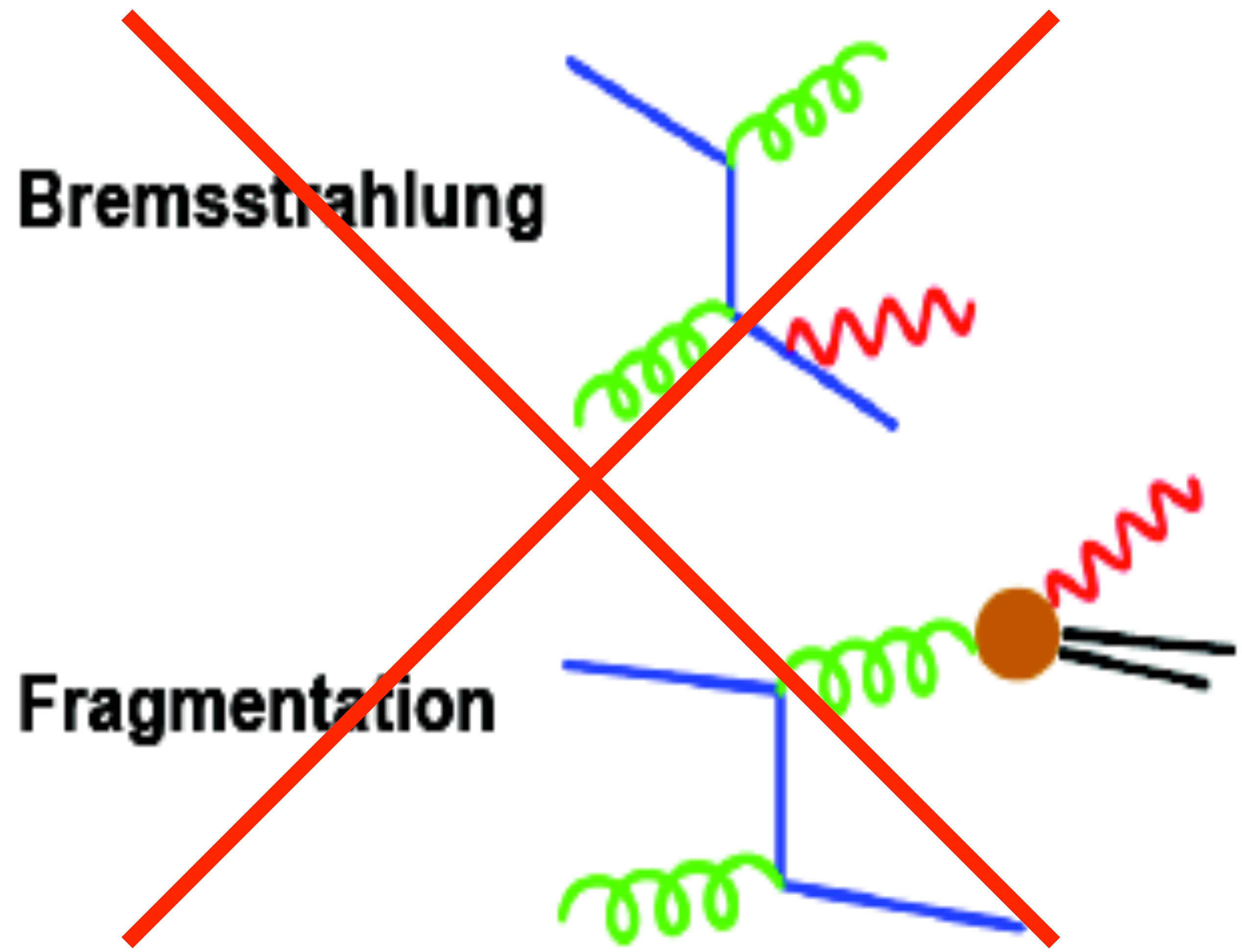
Isolated Photons

Compton

Annihilation

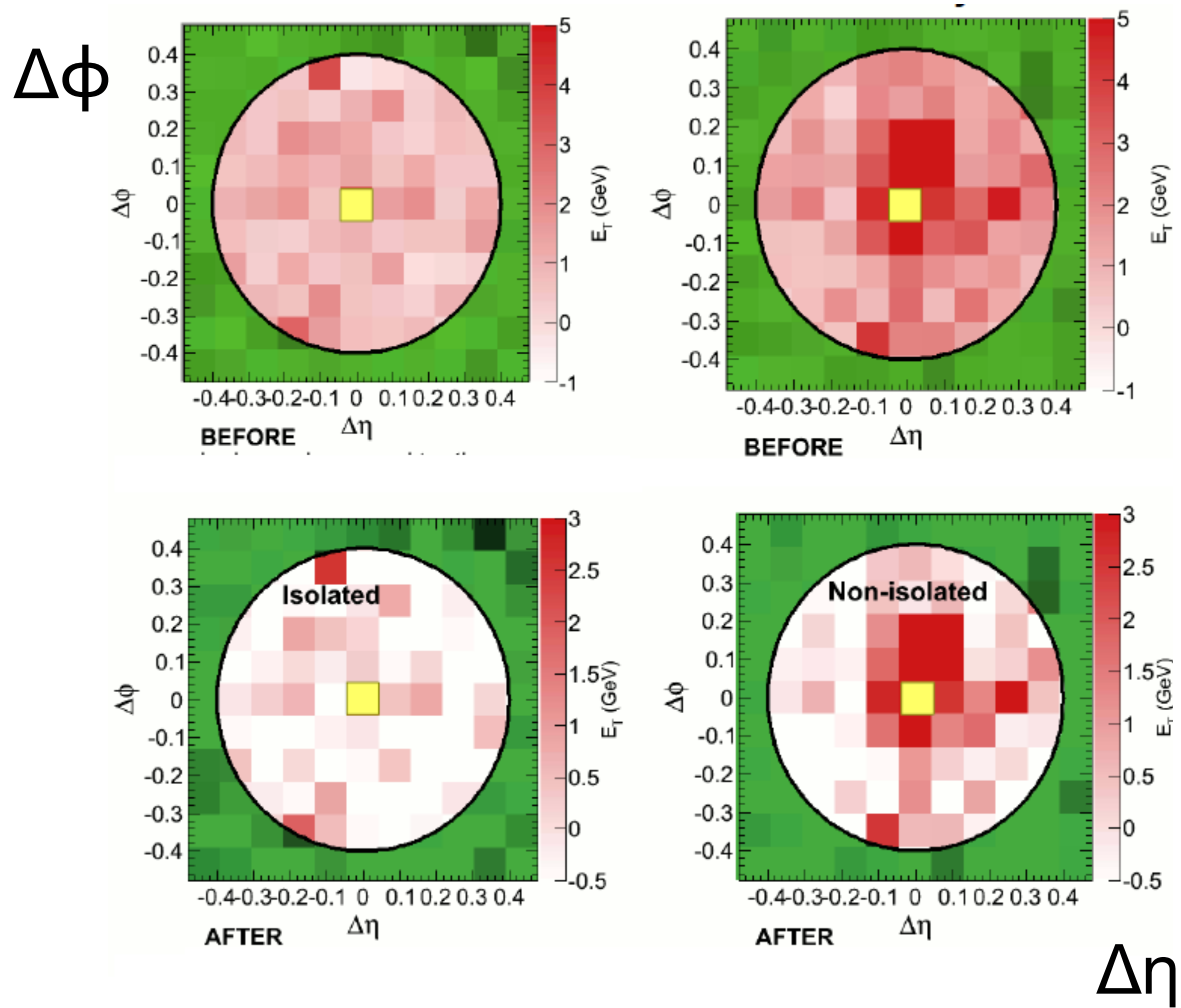


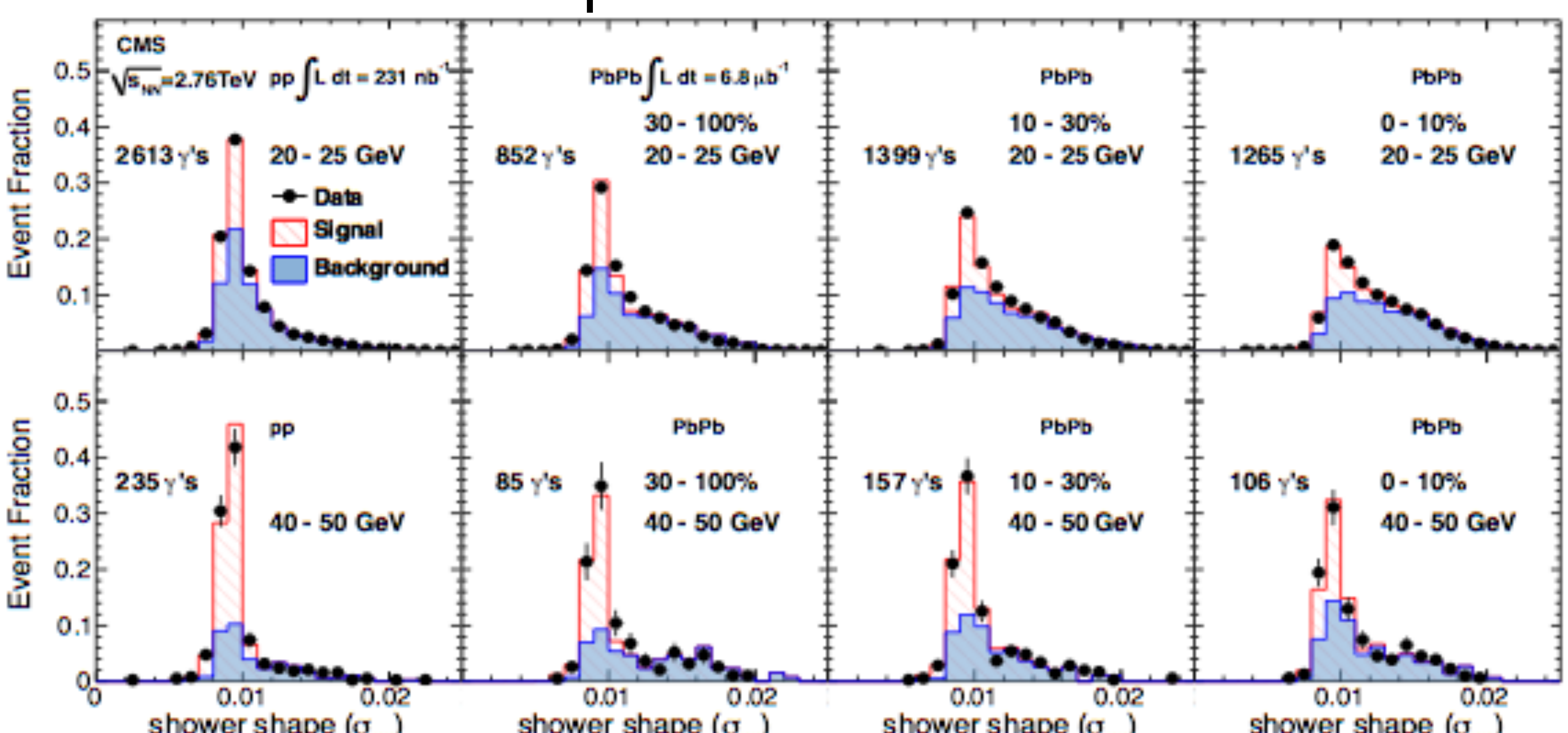
Non-Isolated Photons

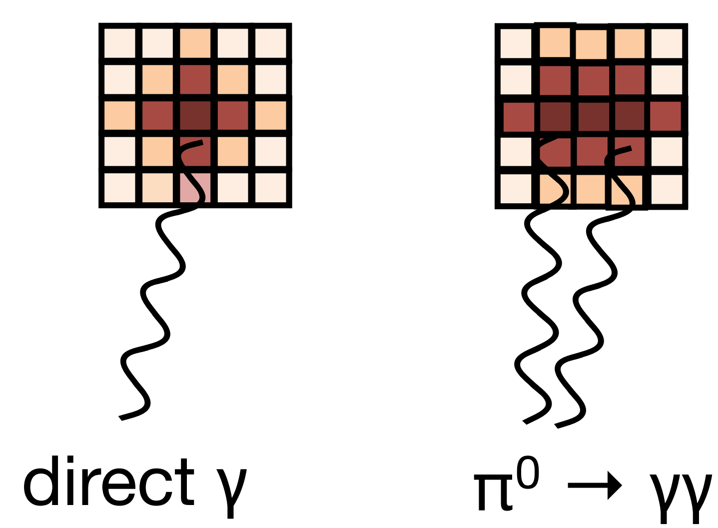


How to Find Isolated Photons?

- Trigger on ECAL clusters
  - fully efficient for $E_T > 20$ GeV
- Subtract underlying event
  - estimate event-by-event from same η strip
- Consider only isolated clusters
  - remove bremsstrahlung and jet fragmentation
- Fit shower shape





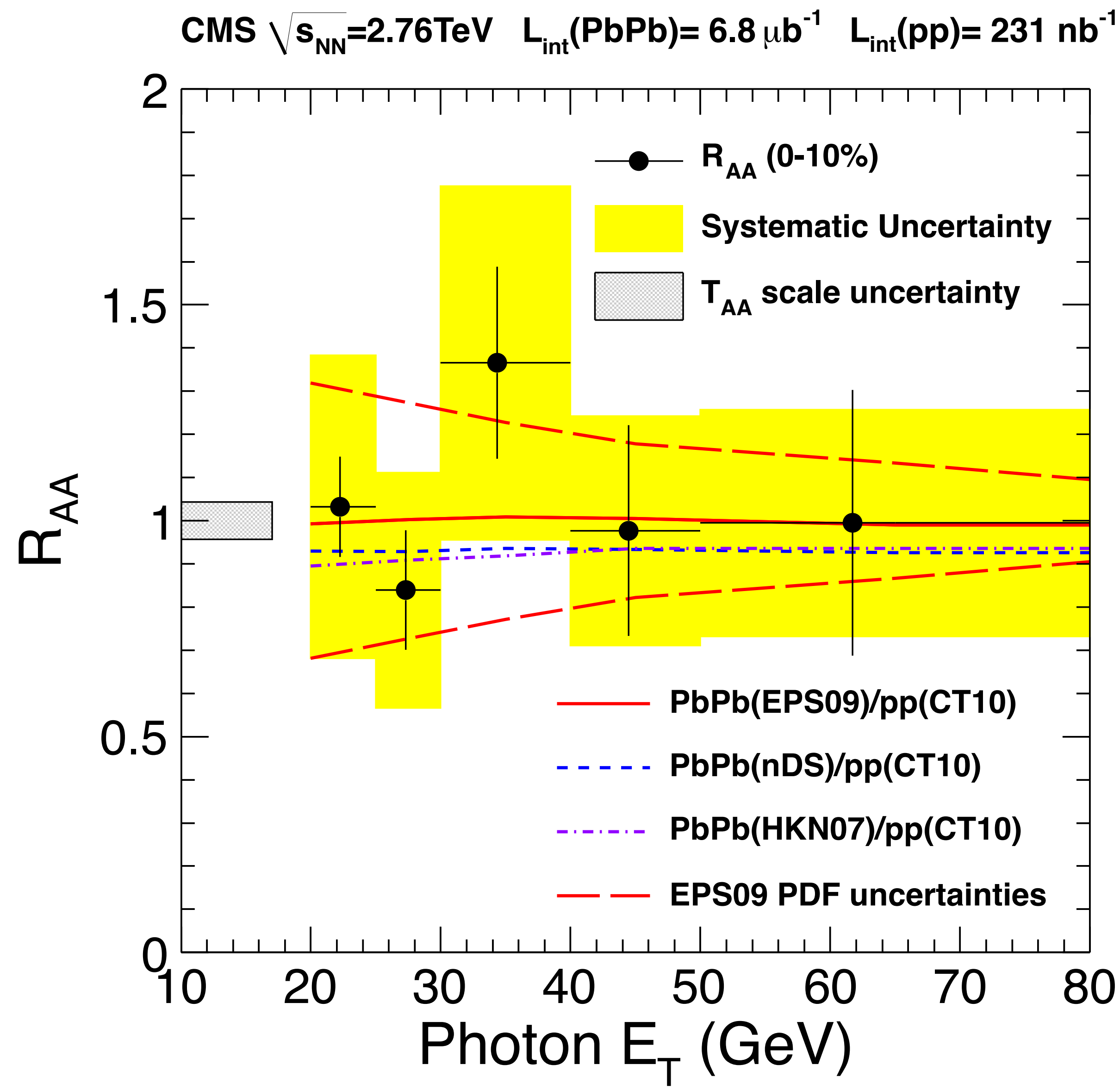


CMS HIN-11-002
PLB 710 (2012) 256

Isolated Photon R_{AA}

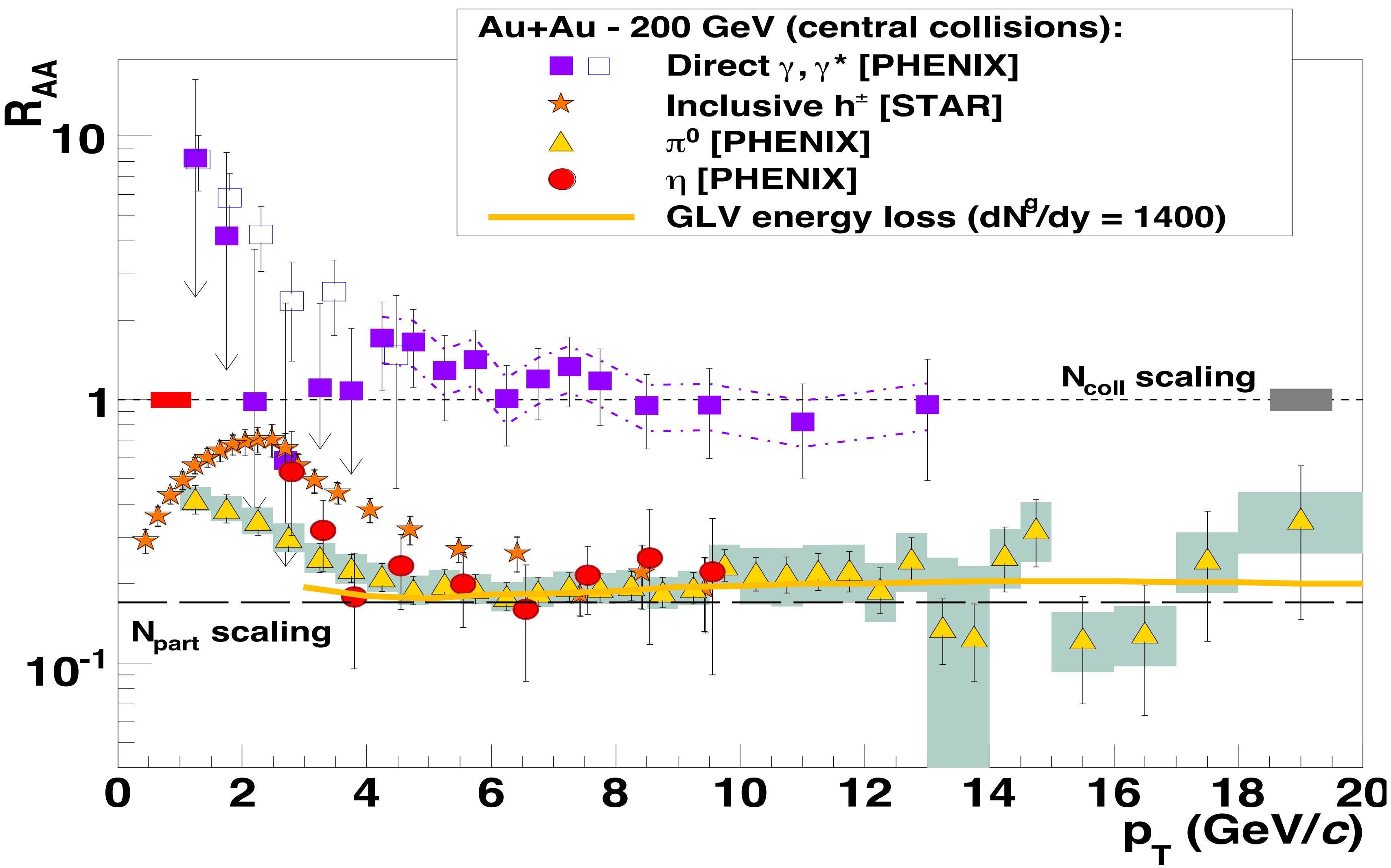
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{\text{coll}} \cdot dN_{pp}/dp_T} \begin{cases} > 1 & \text{enhancement} \\ = 1 & \text{no medium effect} \\ < 1 & \text{suppression} \end{cases}$$

- Normalised by pp data
- Consistent with binary scaling
  - photons are unmodified
- Uncertainties dominated by background
  - not precise enough (yet) to constrain nuclear PDFs

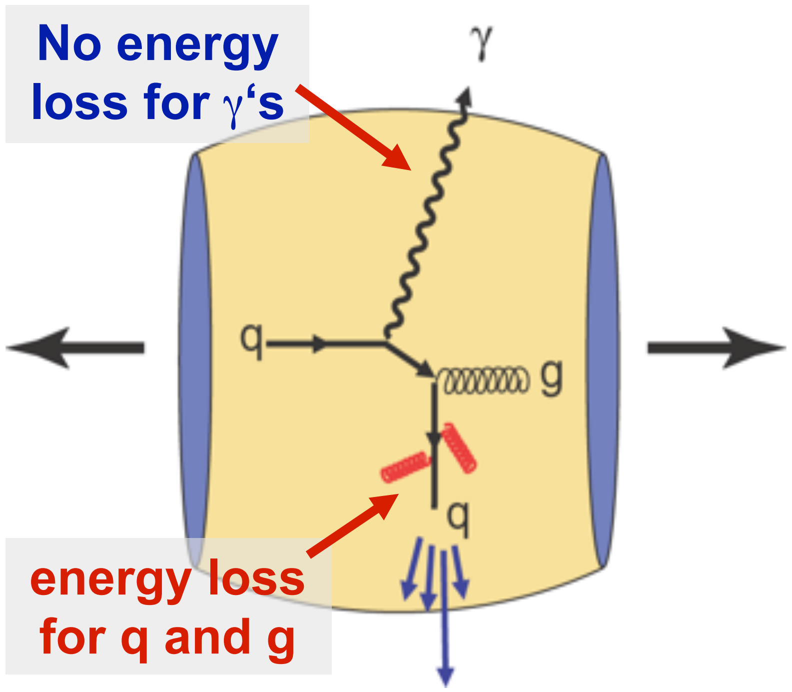


CMS HIN-11-002
PLB 710 (2012) 256

Hadron Suppression



PHENIX: PRL 88 (2002) 022301
PHENIX: PRL 91 (2003) 072301
PHENIX, PRL 94 (2005) 232301
PHENIX, PRL 101 (2008) 232301
STAR, PRL 89 (2002) 202301
STAR, PRL 90 (2003) 082302
STAR, PRL 91 (2003) 172302



- Direct photons are not suppressed: binary scaling for unmodified probes
- **π^0 strongly suppressed by a factor of 5**
  - only hadrons produced on the surface escape (N_{part} scaling)
- Same suppression for other hadrons (e.g. η) at high p_T
  - indicates that suppression occurs at parton level and not during fragmentations

Simple Model for constant R_{AA} vs. p_T

- Pion spectrum in pp: power law

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \frac{1}{p_T^n}$$

  - RHIC pp data well described with n~8

- Constant fractional energy loss:

$$\varepsilon_{\text{loss}} = -\frac{\Delta p_T}{p_T} \Rightarrow p'_T = (1-\varepsilon_{\text{loss}})p_T$$

  - though expect $\varepsilon_{\text{loss}} \propto \frac{\ln p_T}{p_T}$ from QCD

- Modified spectrum

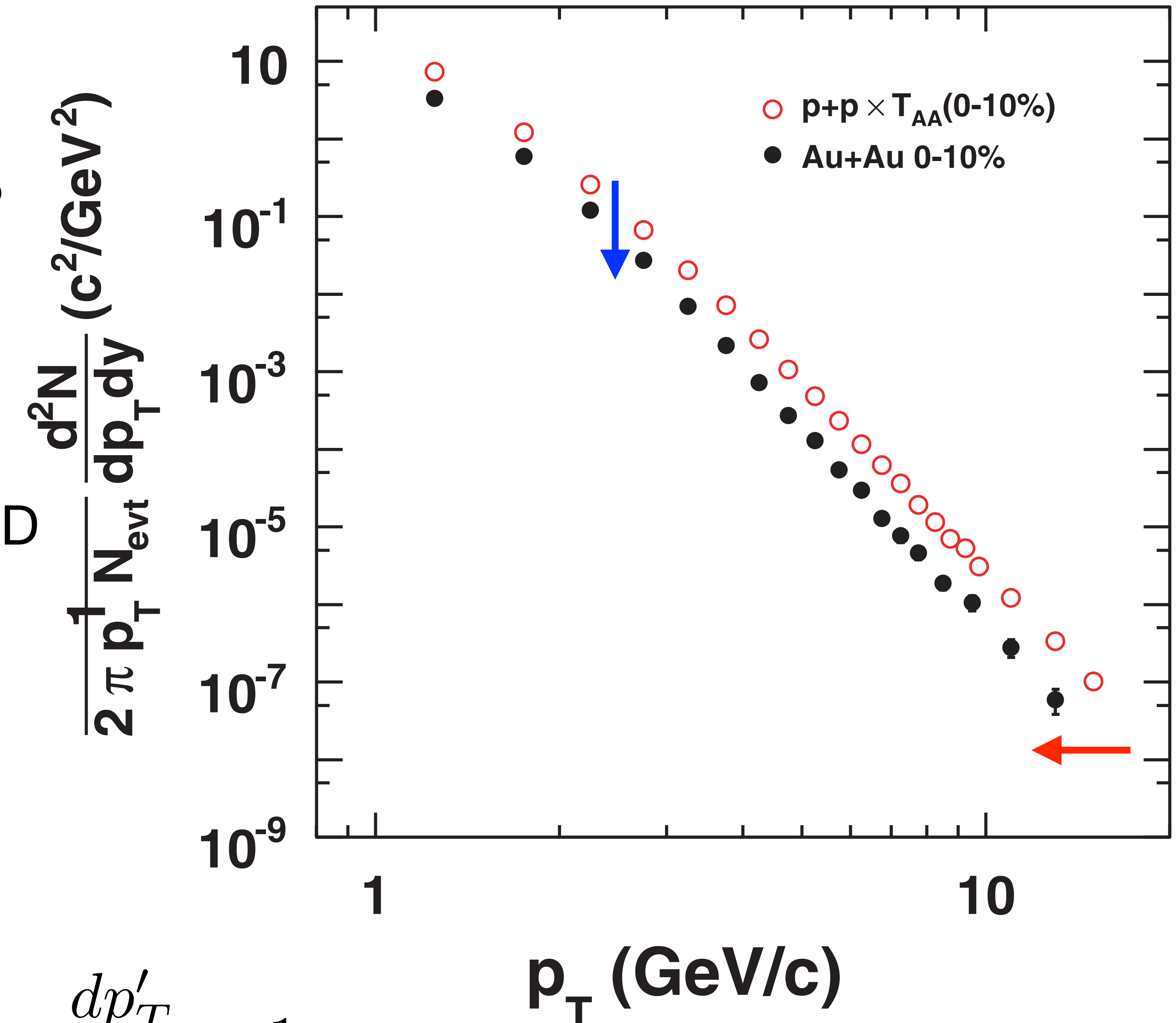
$$\frac{1}{p'_T}\frac{dN}{dp'_T} \propto \frac{1}{p'^{\,n}_T}$$

- Nuclear modification factor

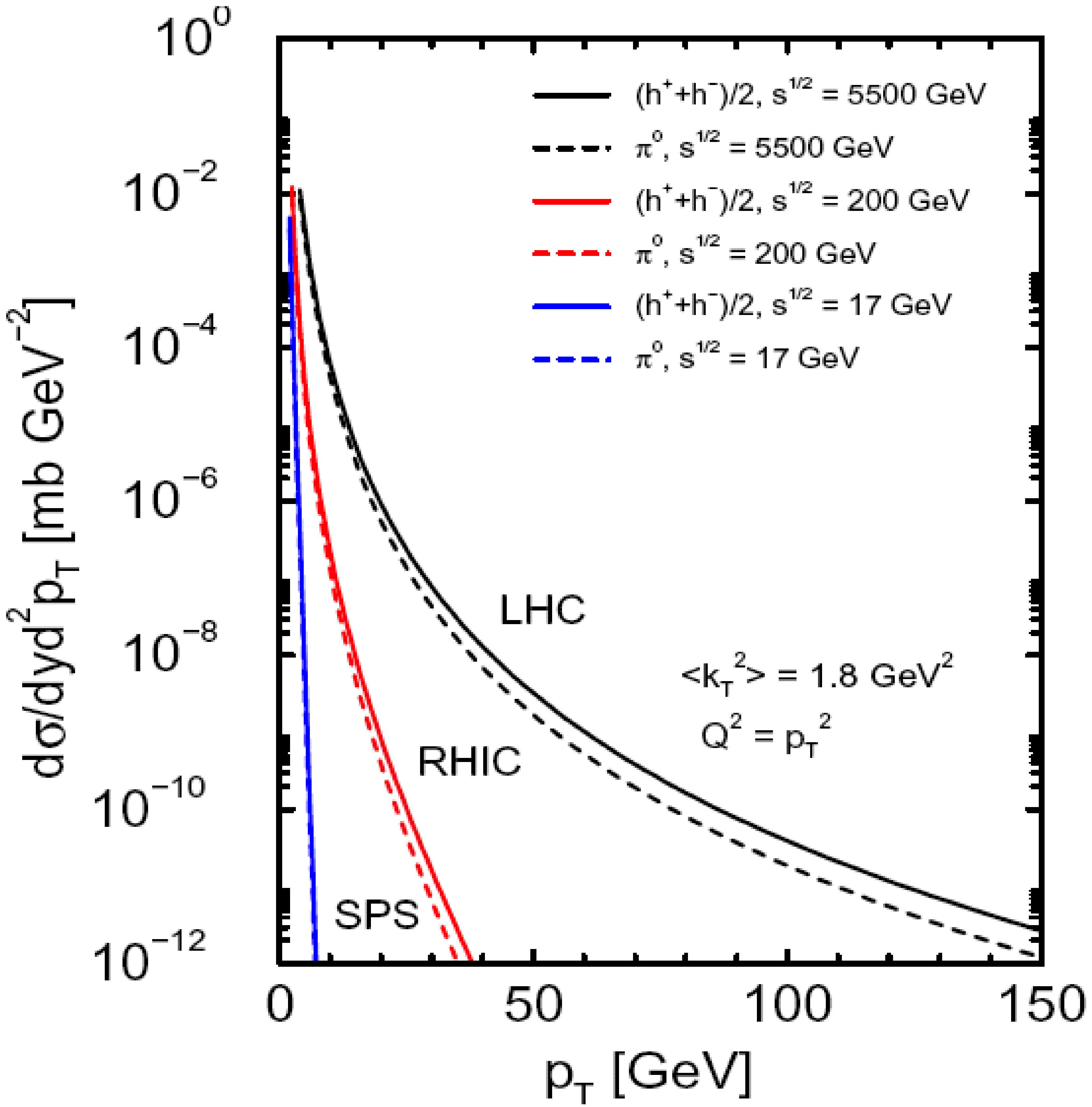
$$R_{AA} = \frac{dN/dp'_T}{dN/dp_T} = \frac{p'^{\,-n+1}_T}{p_T^{-n+1}}\frac{dp'_T}{dp_T} \quad \Leftarrow \frac{dp'_T}{dp_T} = 1-\varepsilon_{\text{loss}}$$

$$\Rightarrow R_{AA} = (1-\varepsilon_{\text{loss}})^{-n+2} \qquad \Rightarrow \varepsilon_{\text{loss}} = 1 - R_{AA}^{1/n-2} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

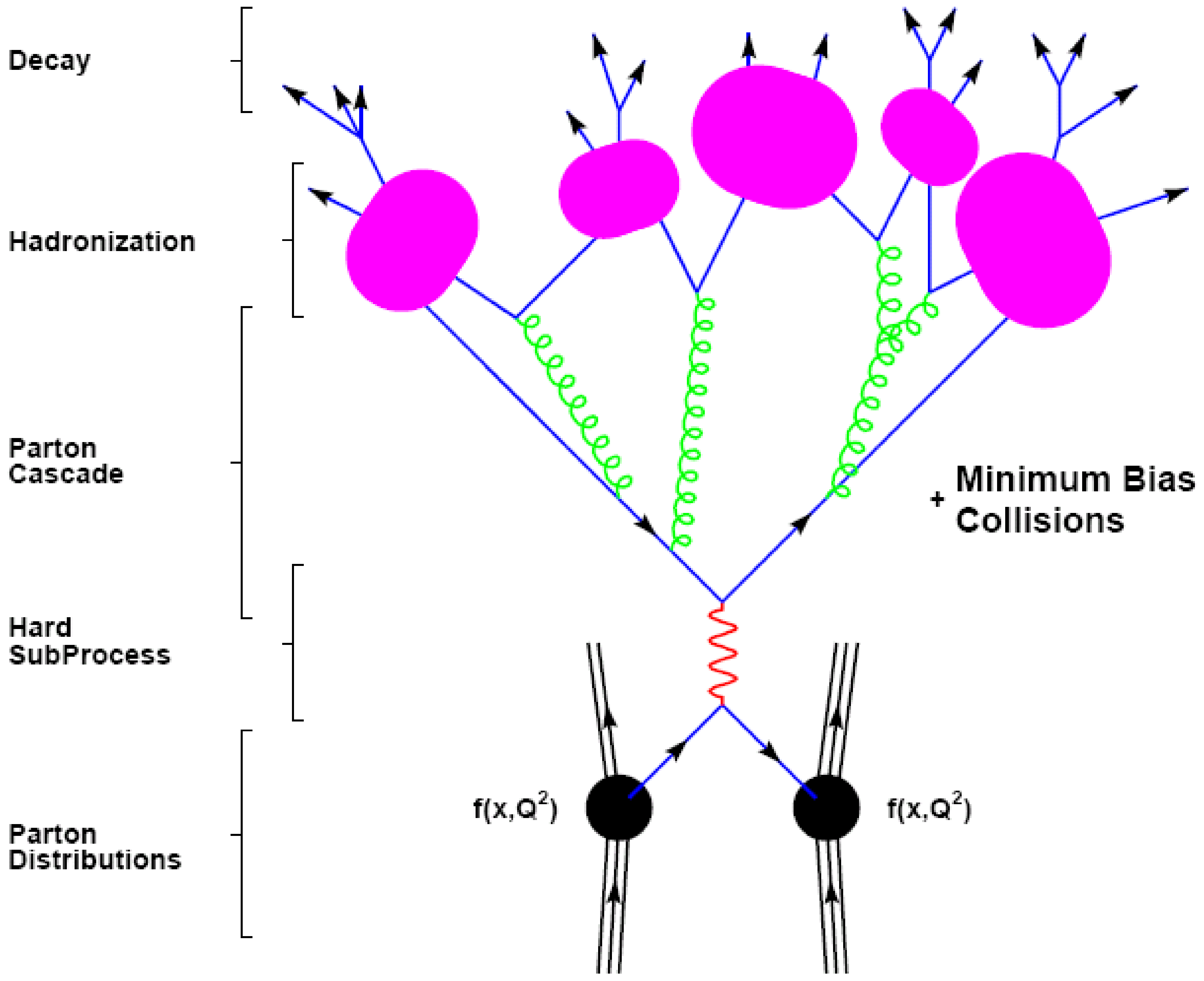
Horizontal shift of spectrum rather than yield suppression



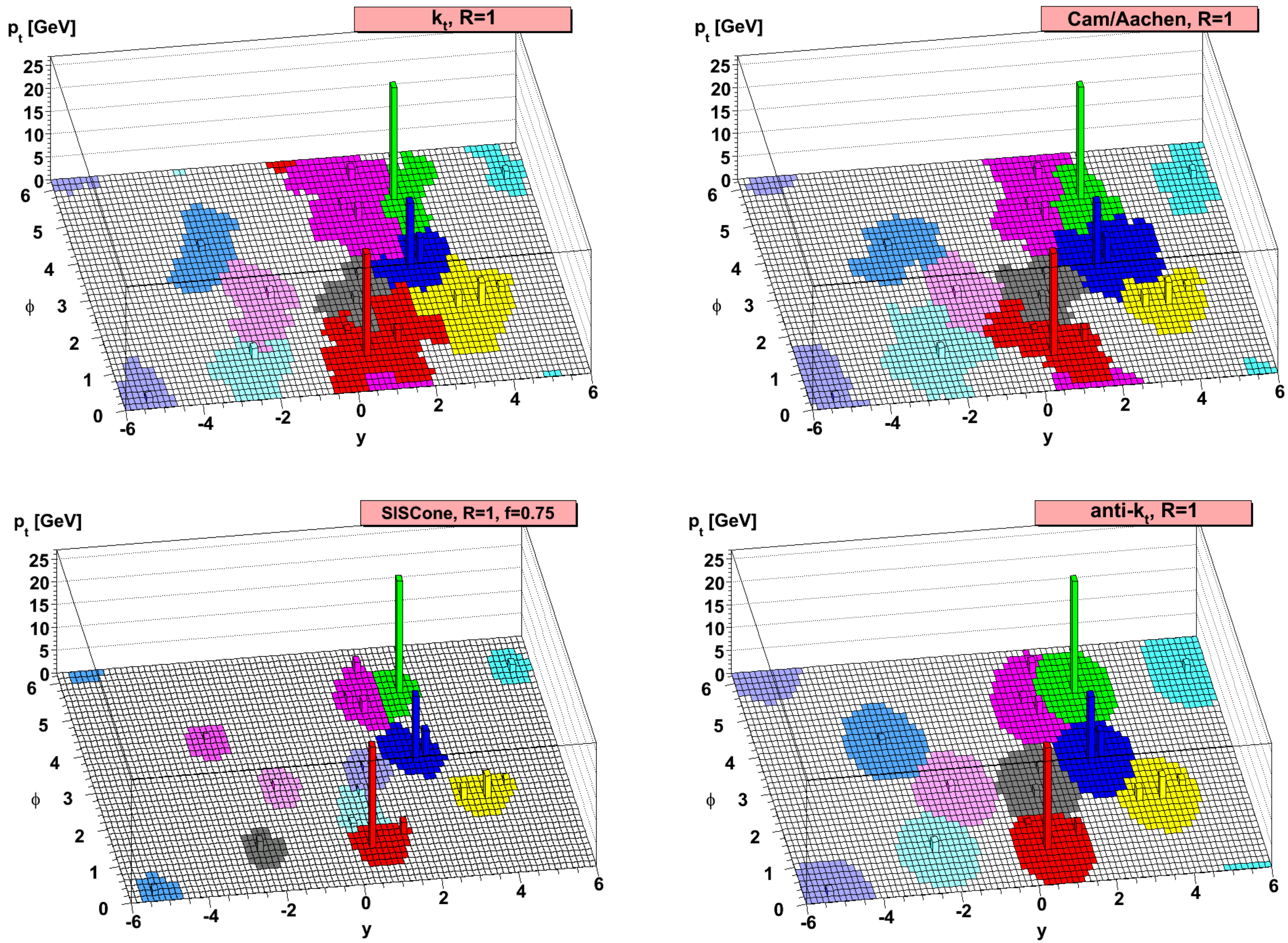
Hard Probes at the LHC



Jet Evolution

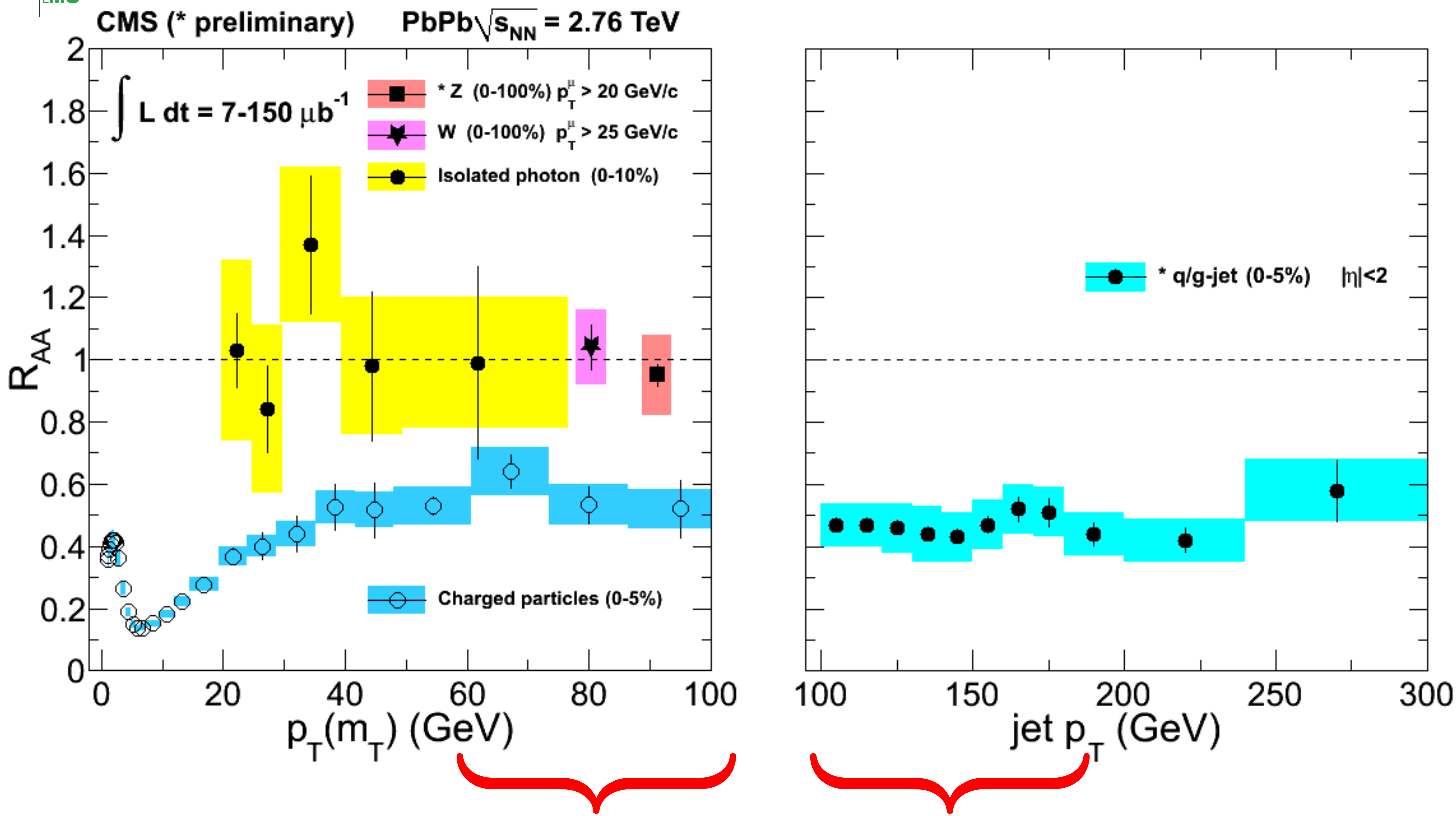


Jet Cluster Algorithms



Cacciari et al., JHEP 04 (2008) 063

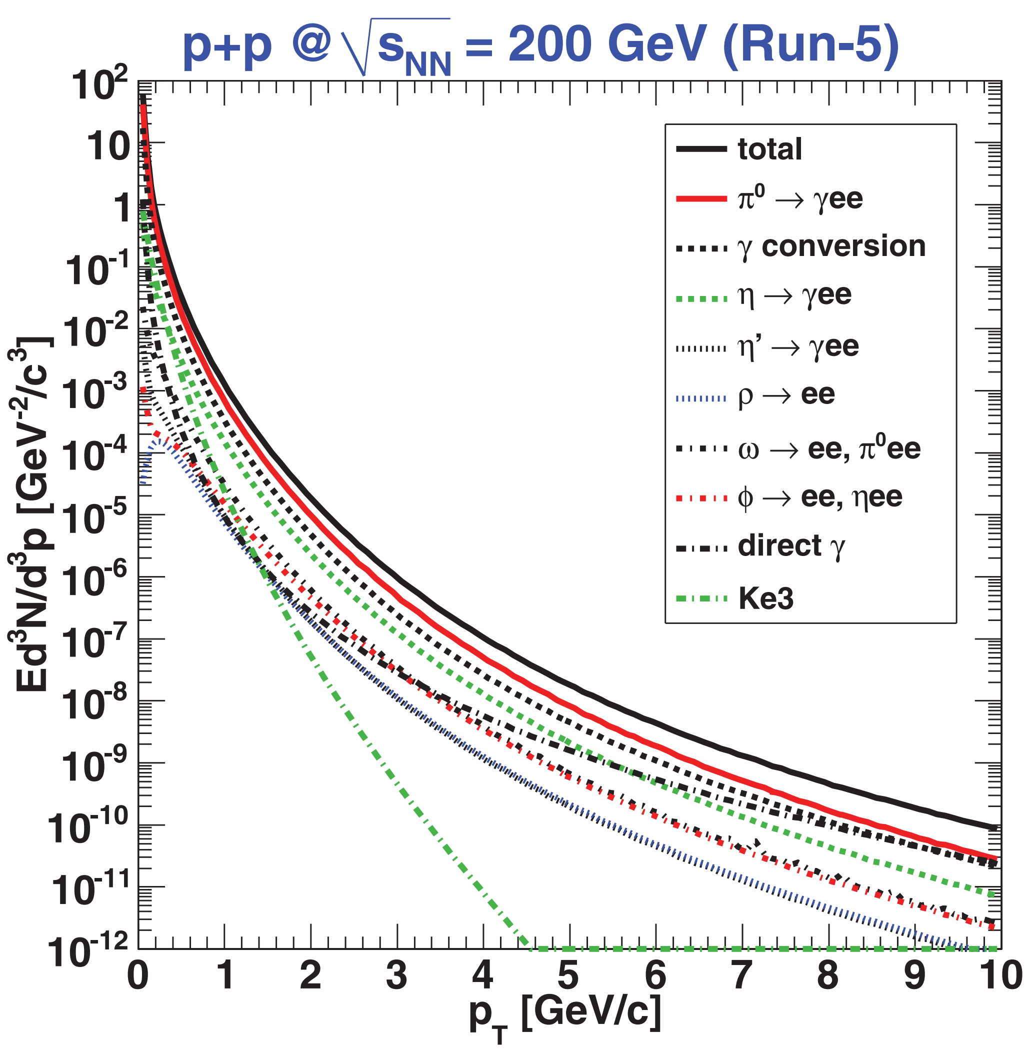
Connecting R_{AA} of Hadrons and Jets



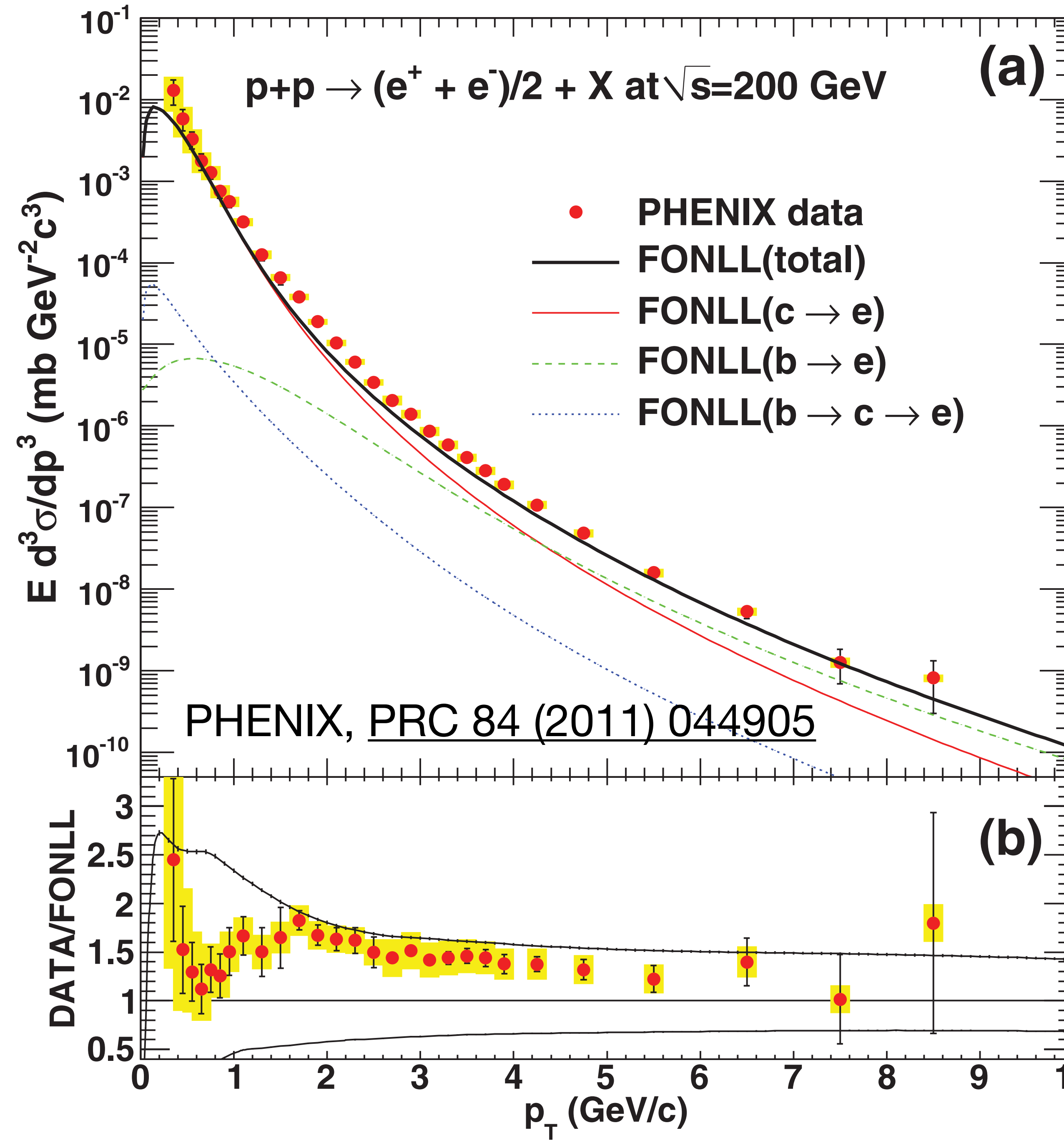
Charged particles from p_T = 50–100 GeV:
typical $z = p_T(\text{track})/p_T(\text{jet})$ = 0.4–0.6

“Non-photonic” electrons

- Measure inclusive electrons
- Subtract “cocktail” of hadron decays
  - as for dileptons
  - hadronic decays via virtual photon → “photonic”

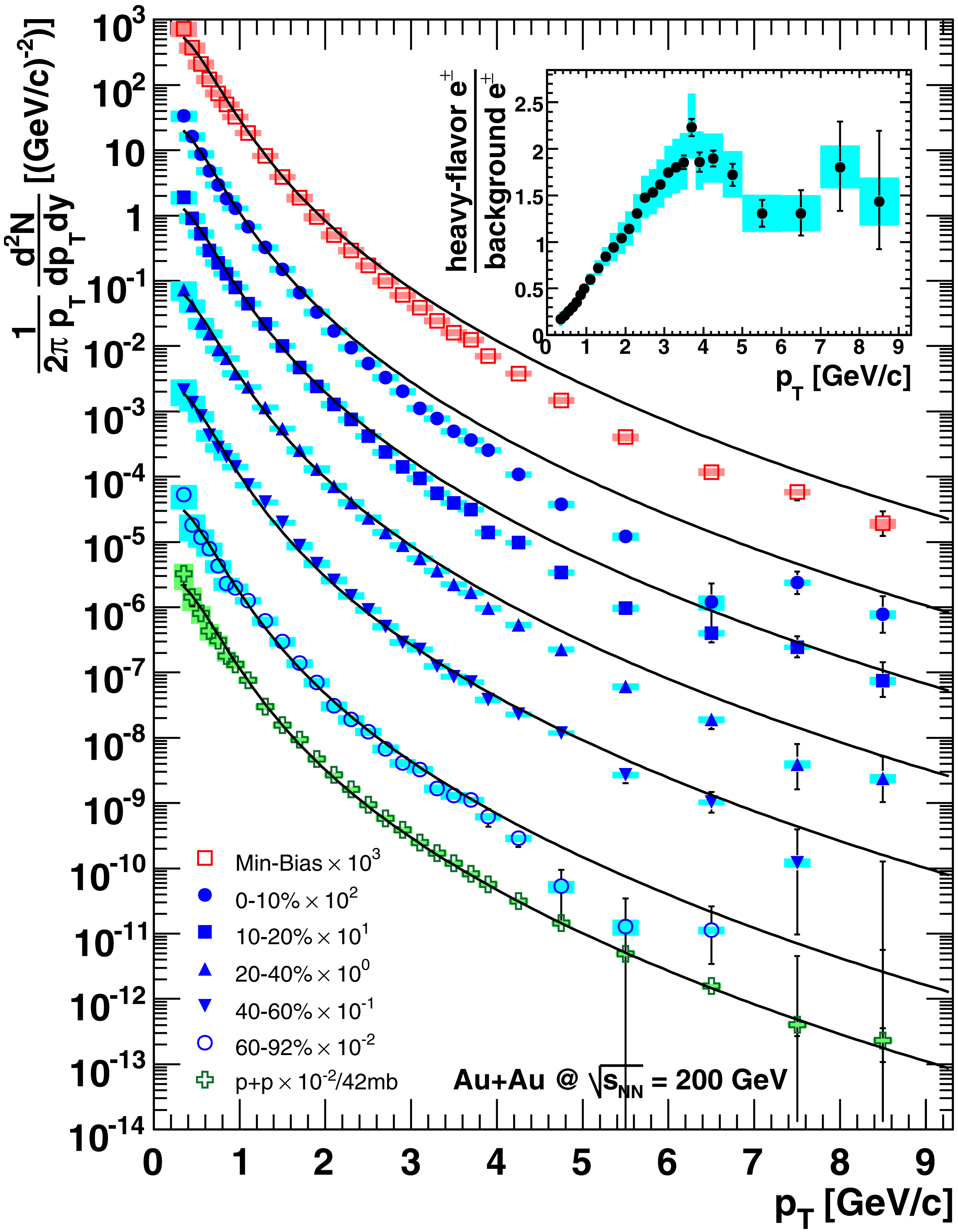


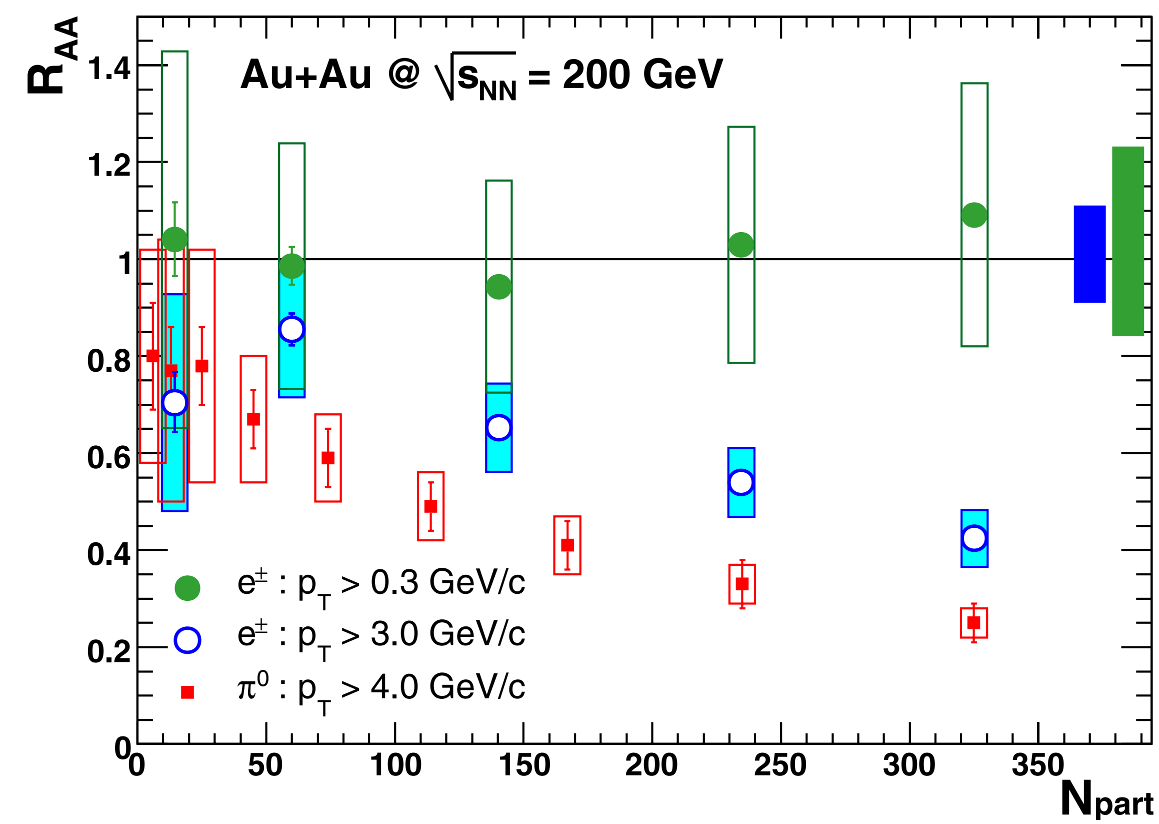
- Result: non-photonic electrons
  - from semileptonic D and B decays



“Non-photonic” electrons

PHENIX, PRC 84 (2011) 044905
PHENIX, PRL 98 (2007) 172301



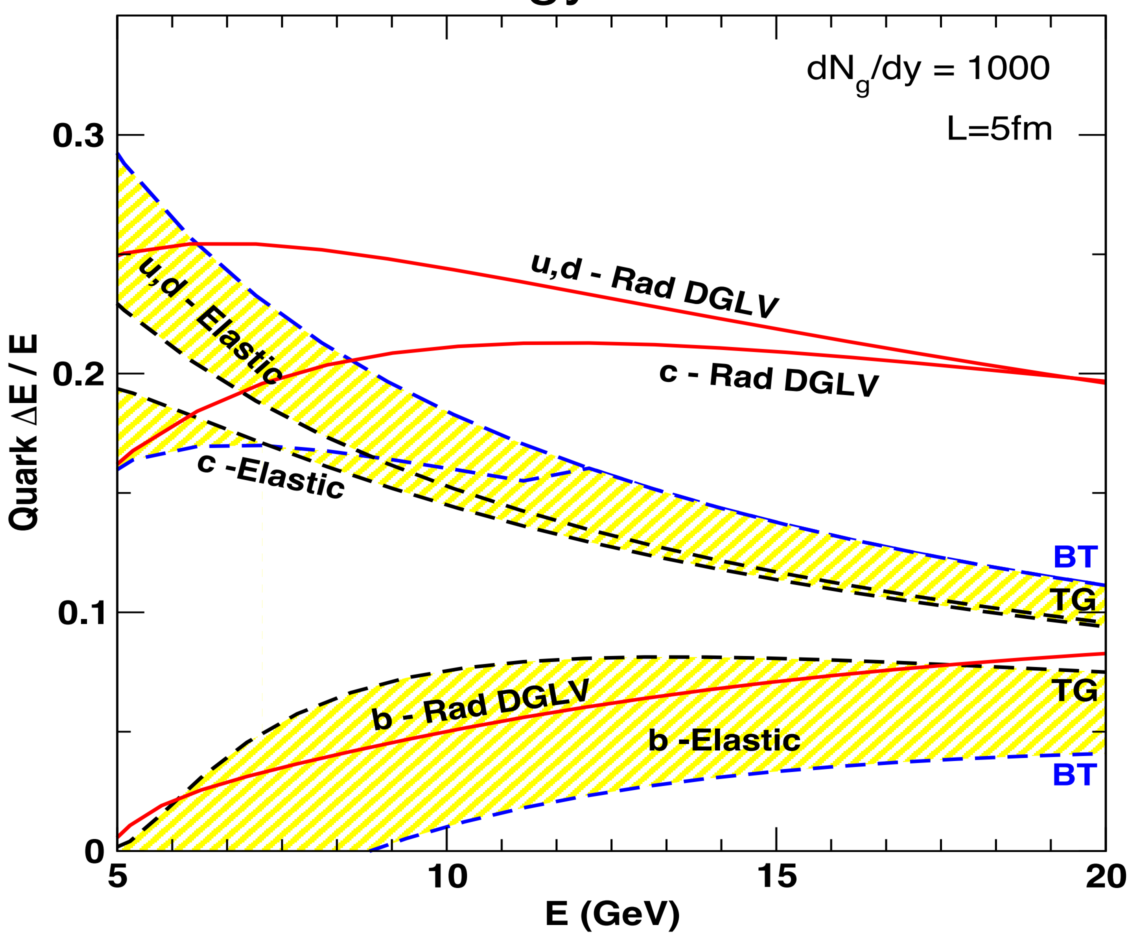


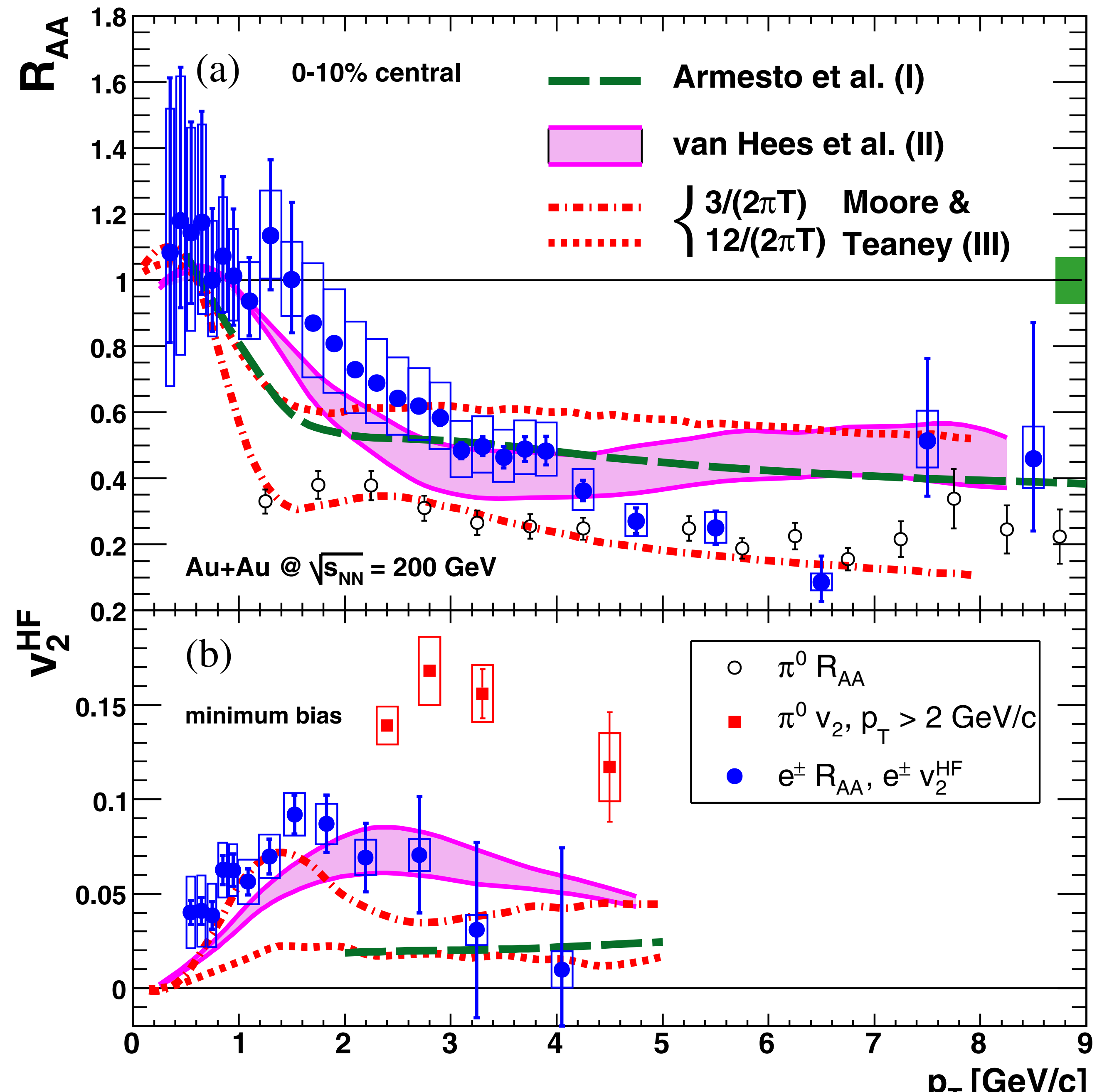
- Total charm cross section scales with number of binary collisions
- Charm suppression at high p_T
  - slightly less suppressed than π^0 as expected from dead cone effect

"Non-photonic" electrons

PHENIX, PRC 84 (2011) 044905
PHENIX, PRL 98 (2007) 172301

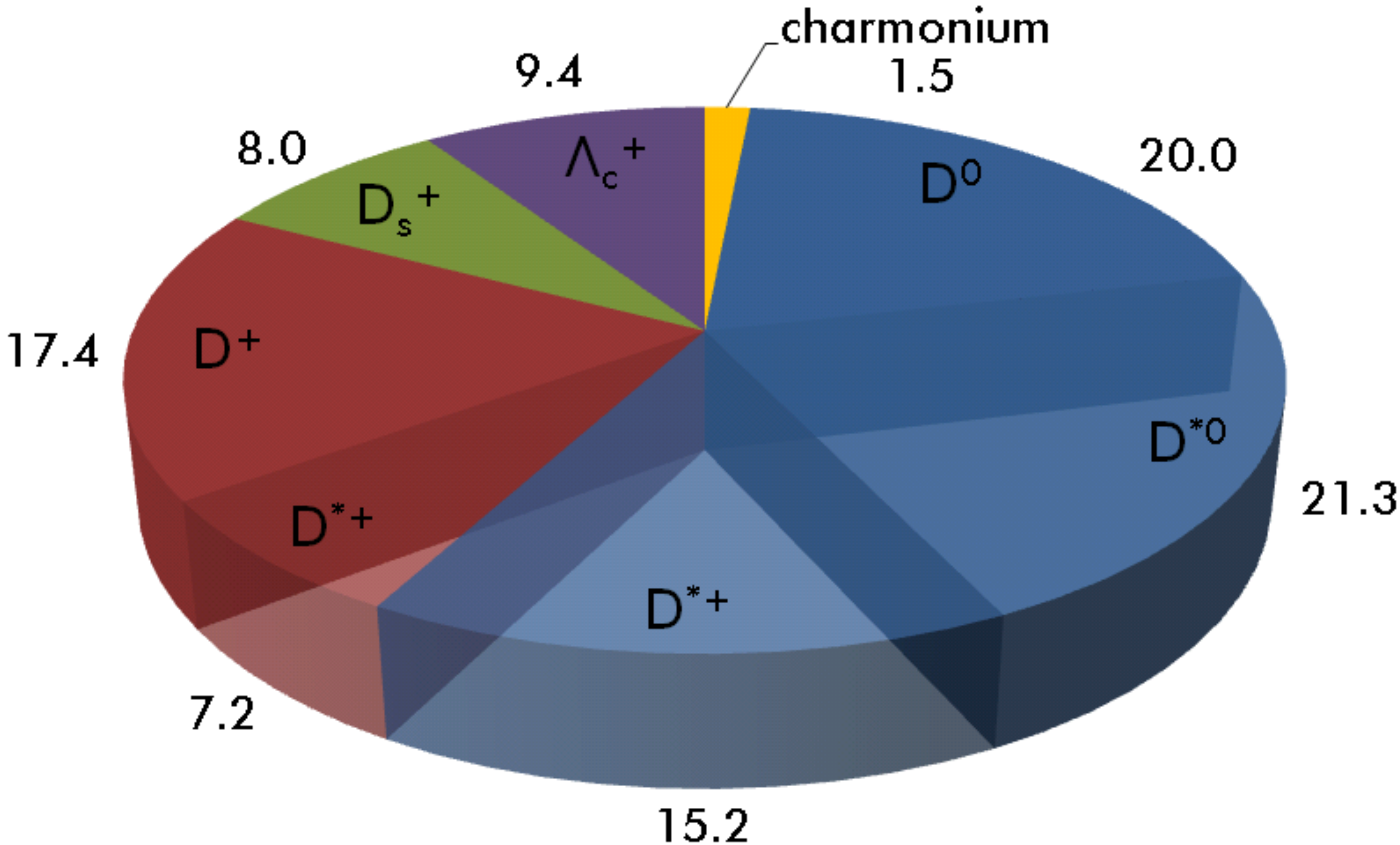
- Strong suppression and elliptic flow challenge for models
  - above ~4 GeV mass ordering of suppression disappears
- Need to include collisional energy loss mechanisms
  - for heavy quarks as large as radiative energy loss





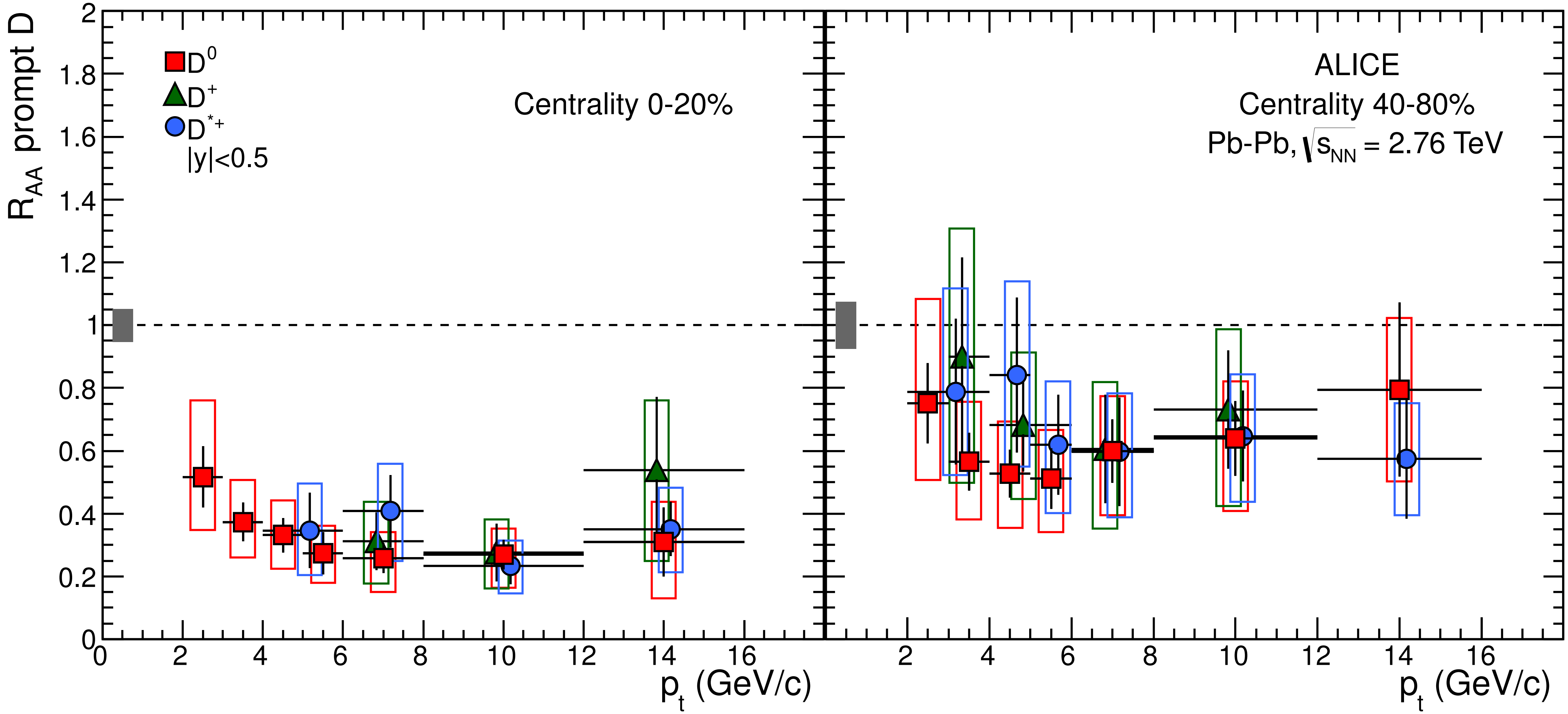
- But no separation of b and c
- What happens to b quarks?

The Charmed Meson Zoo



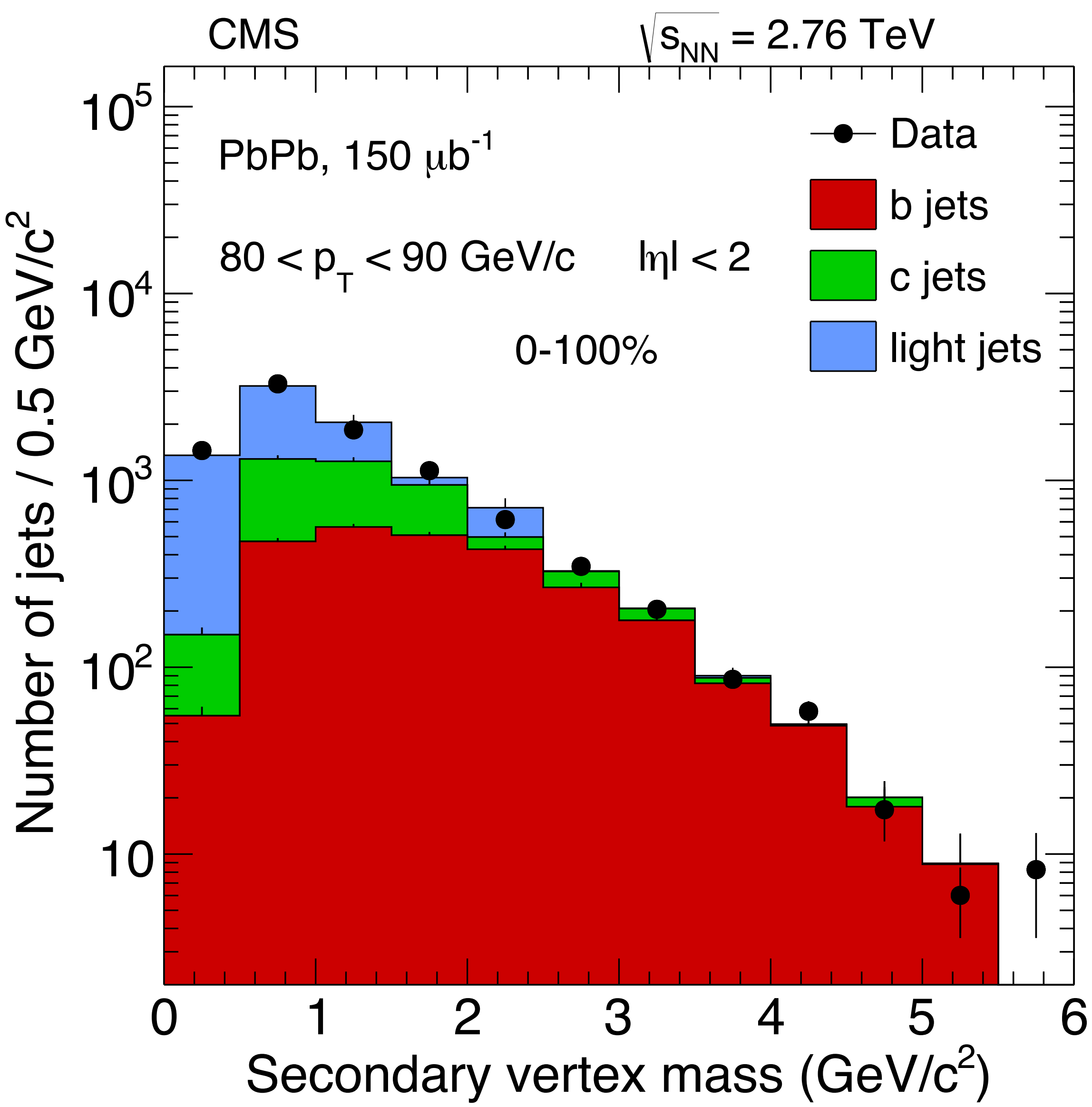
K. Schweda, arXiv:1402.1370

D mesons in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



- Strong suppression of various D mesons up to 16 GeV
  - suppression factor 3–4 in 0–20% centrality
  - less suppression in peripheral collisions

b jets in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

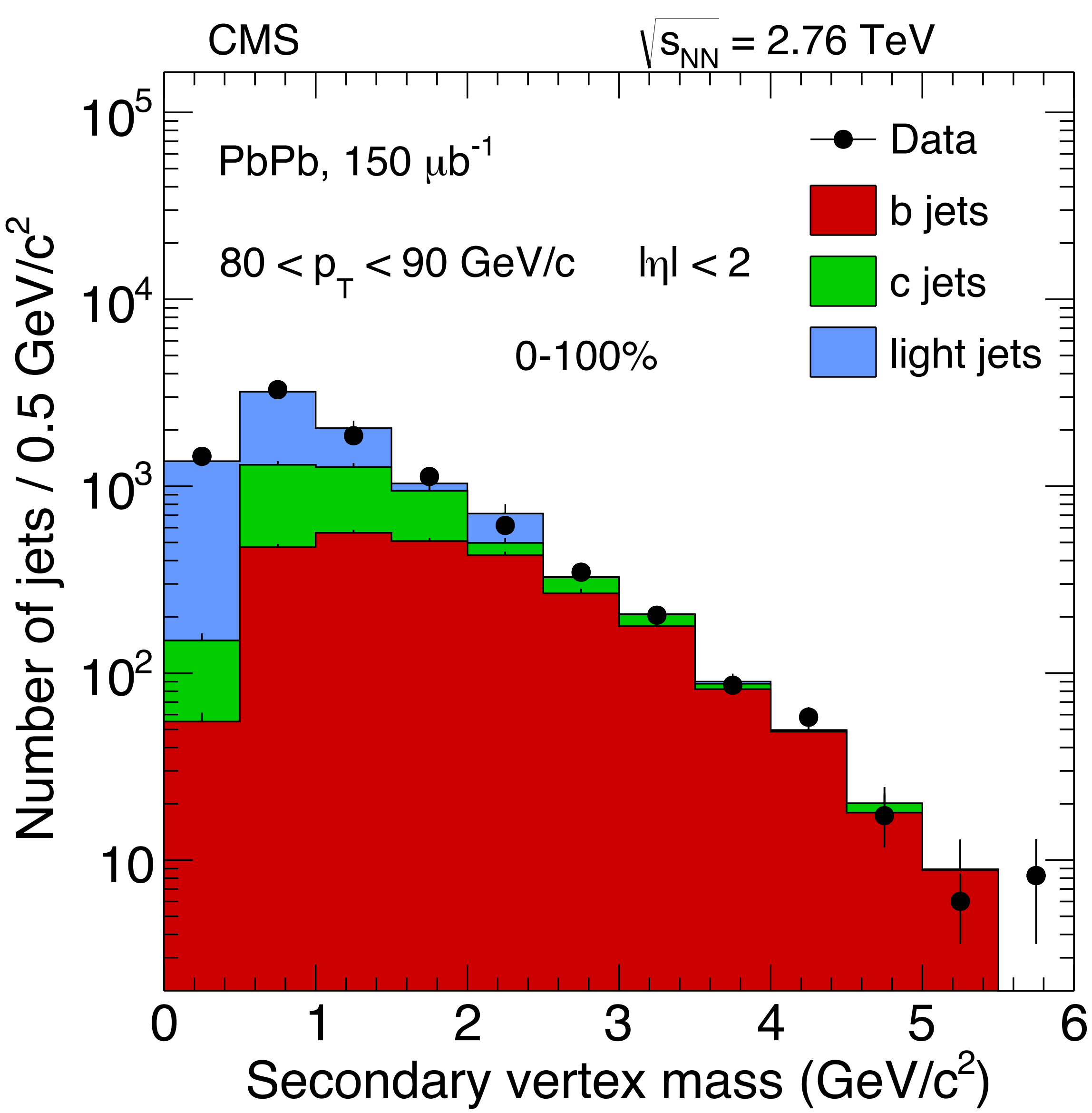


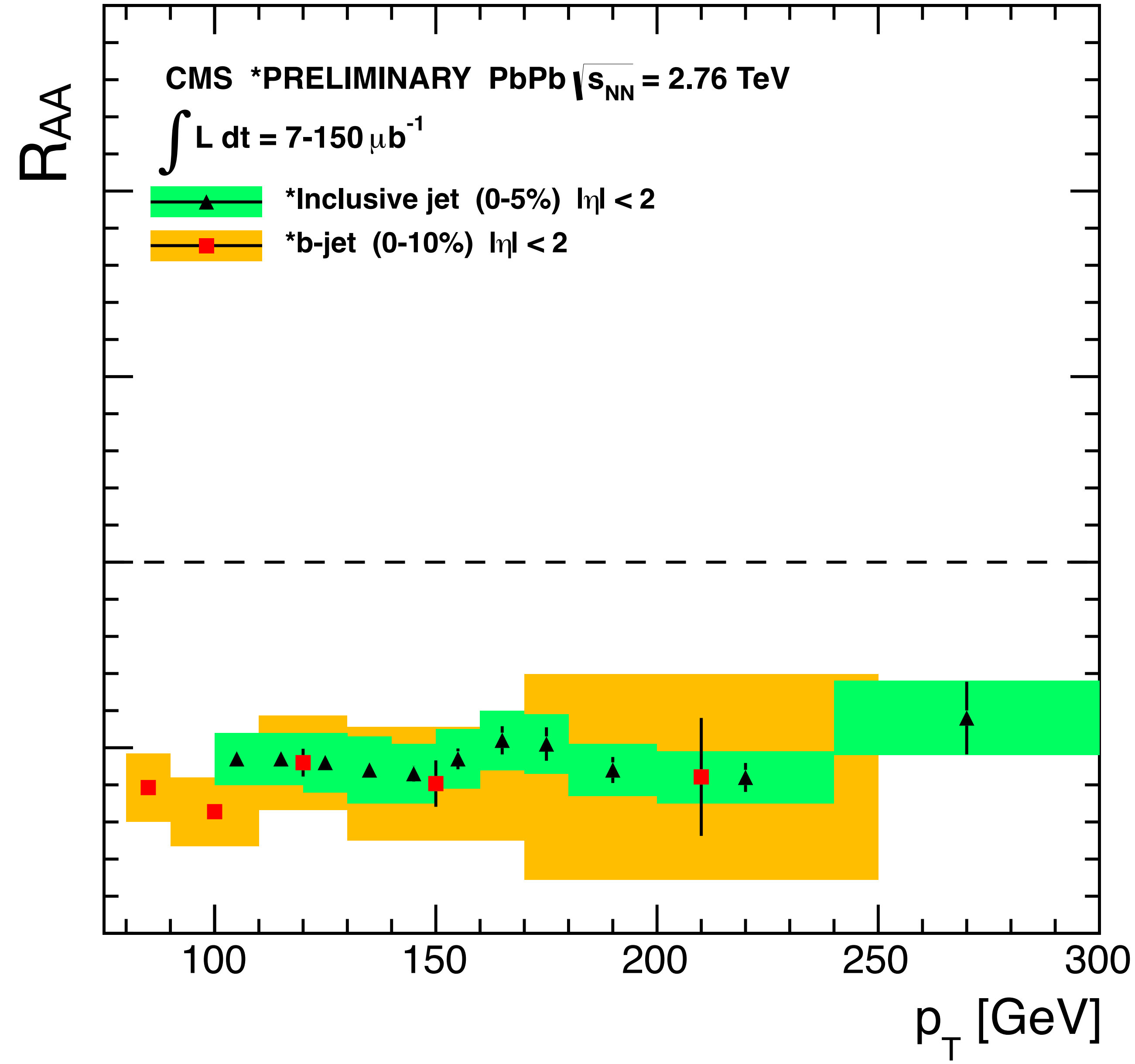
- Identify b jets via the invariant mass of particles forming a secondary vertex
  - $m_B > m_D > m_h$

CMS, PRL 113 (2014) 132301

- b-jets show same suppression in Pb–Pb as light jets
- Favours models with small mass dependence of energy loss

b jets in Pb–Pb at $\sqrt{s_{NN}}$ = 2.76 TeV





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CMS, PRL 113 (2014) 132301

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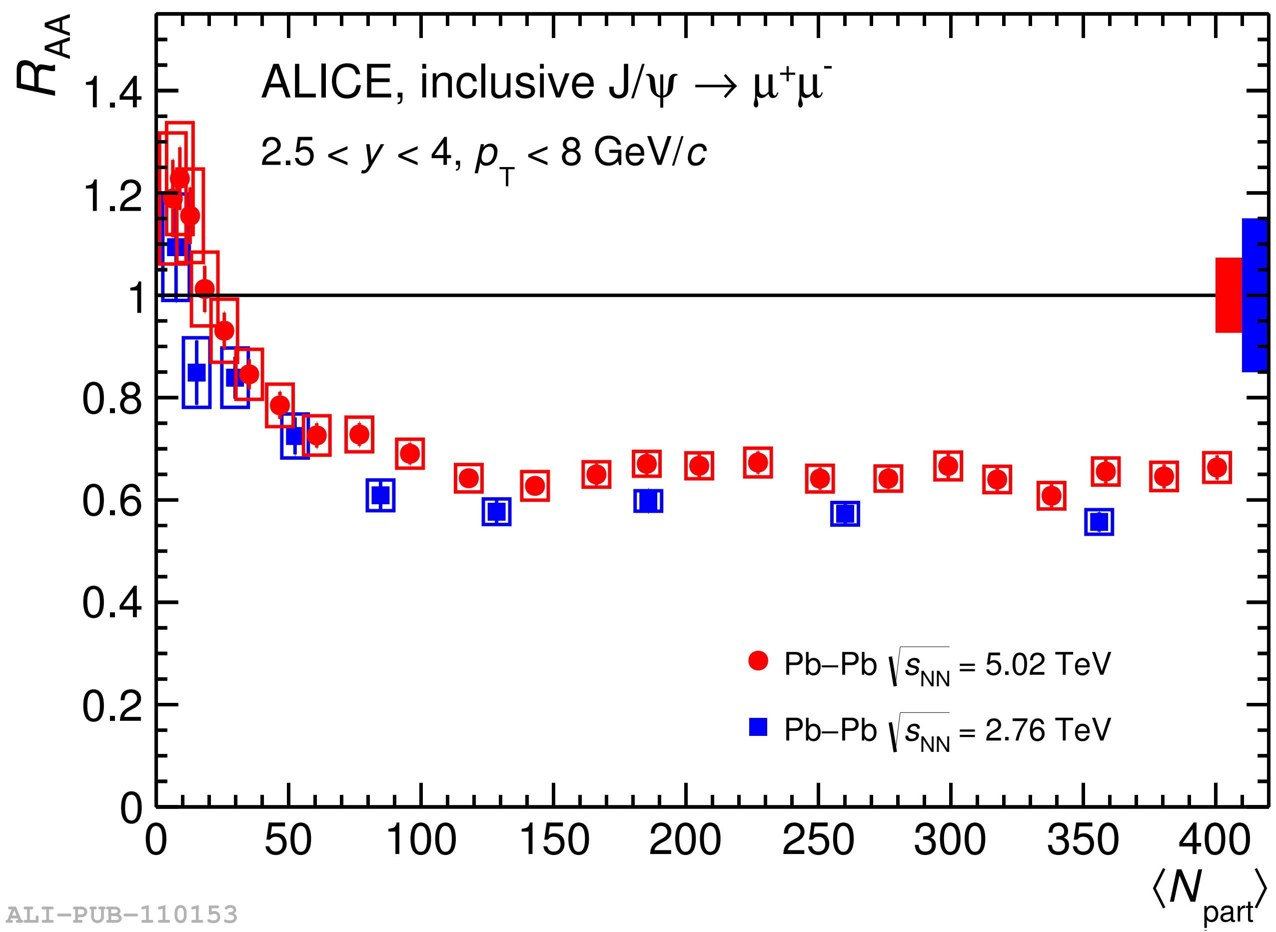
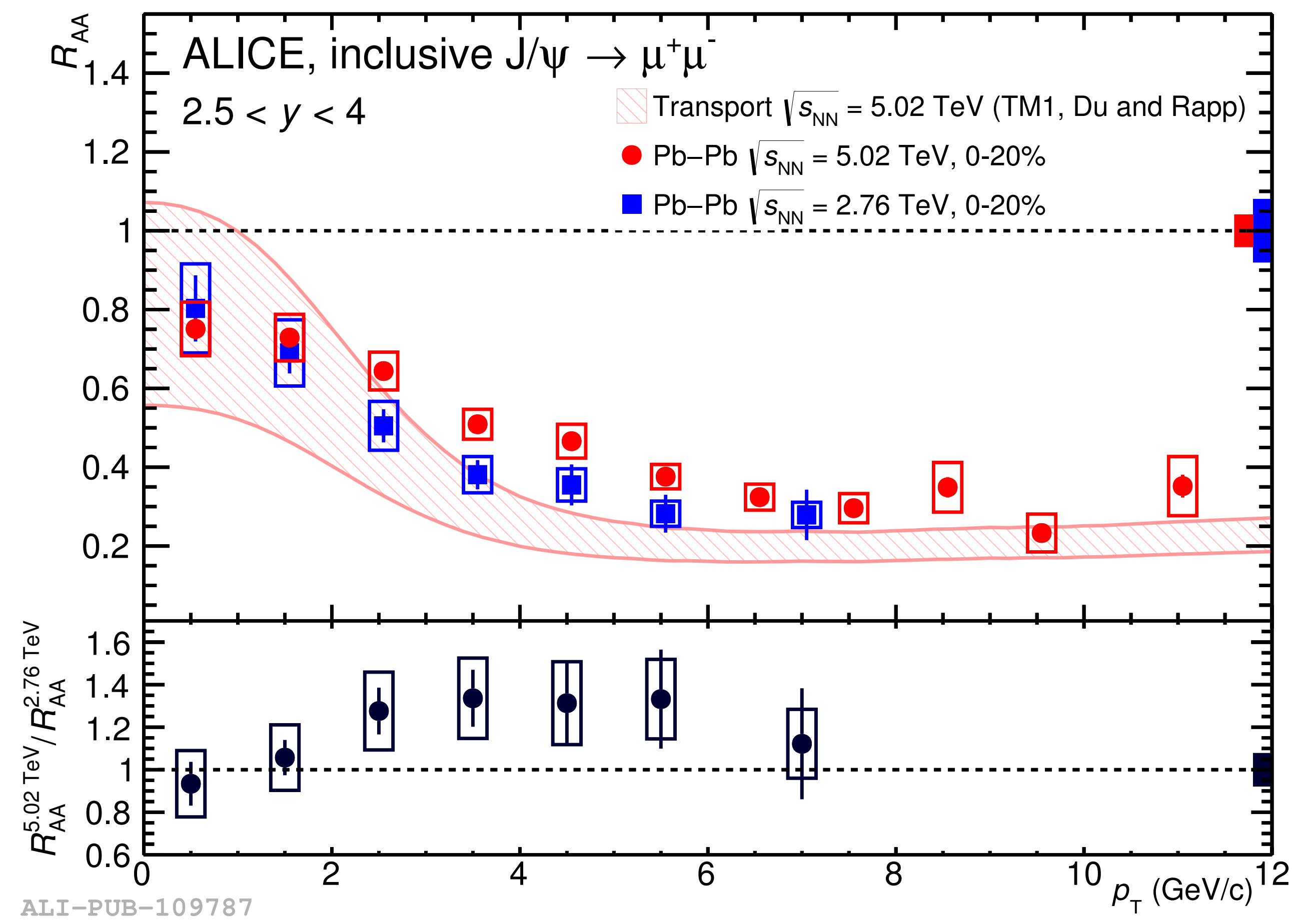
Low pT J/ψ

ALICE, arXiv:1606.08197
(submitted to PLB)





- Centrality independent increase from 2.76 TeV to 5.02 TeV (<1σ)
  - expected from regeneration as charm cross section increases by ~10%
- No change at low pT
- **Increase for pT>2 GeV, regeneration + radial flow effects?**

Low pT J/ψ

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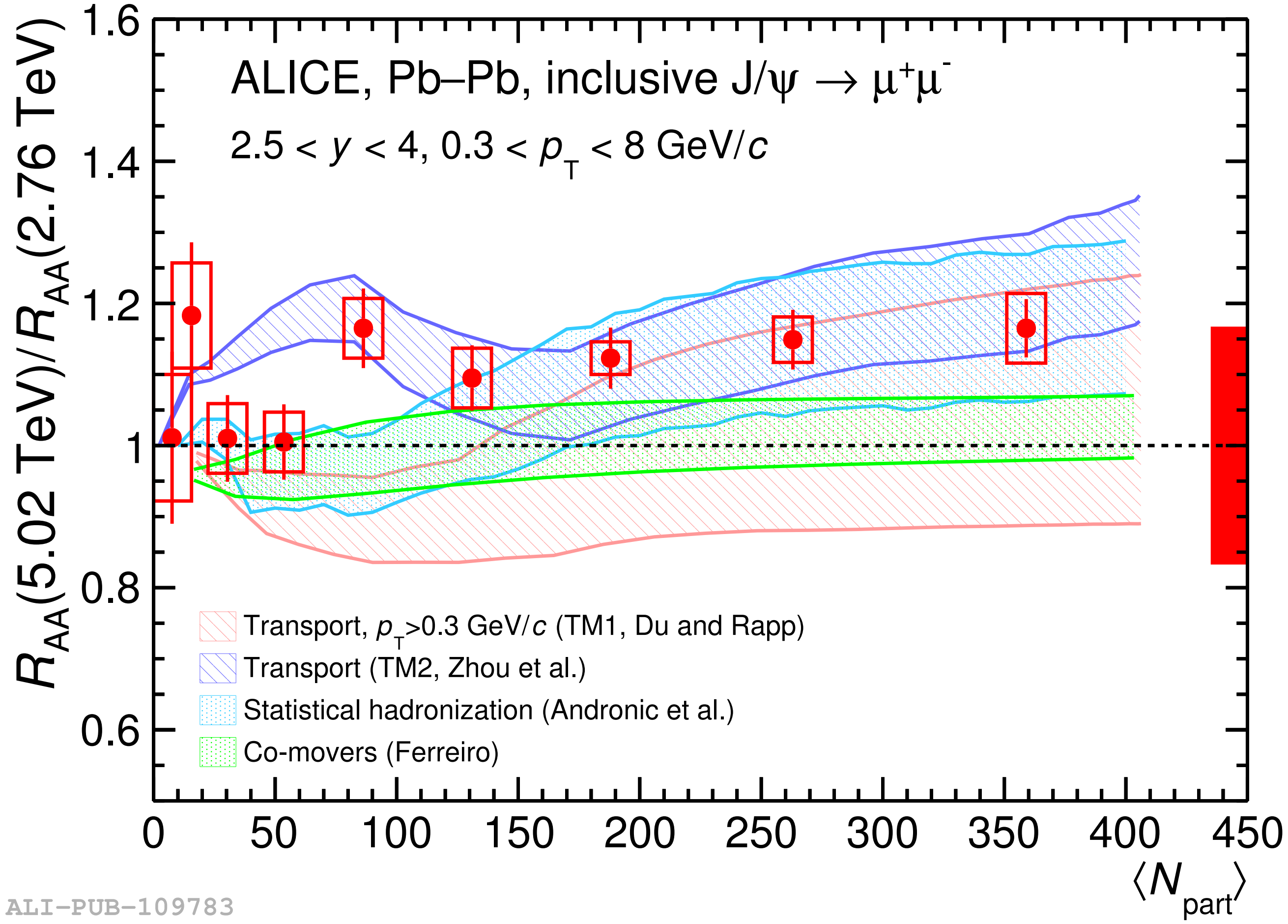

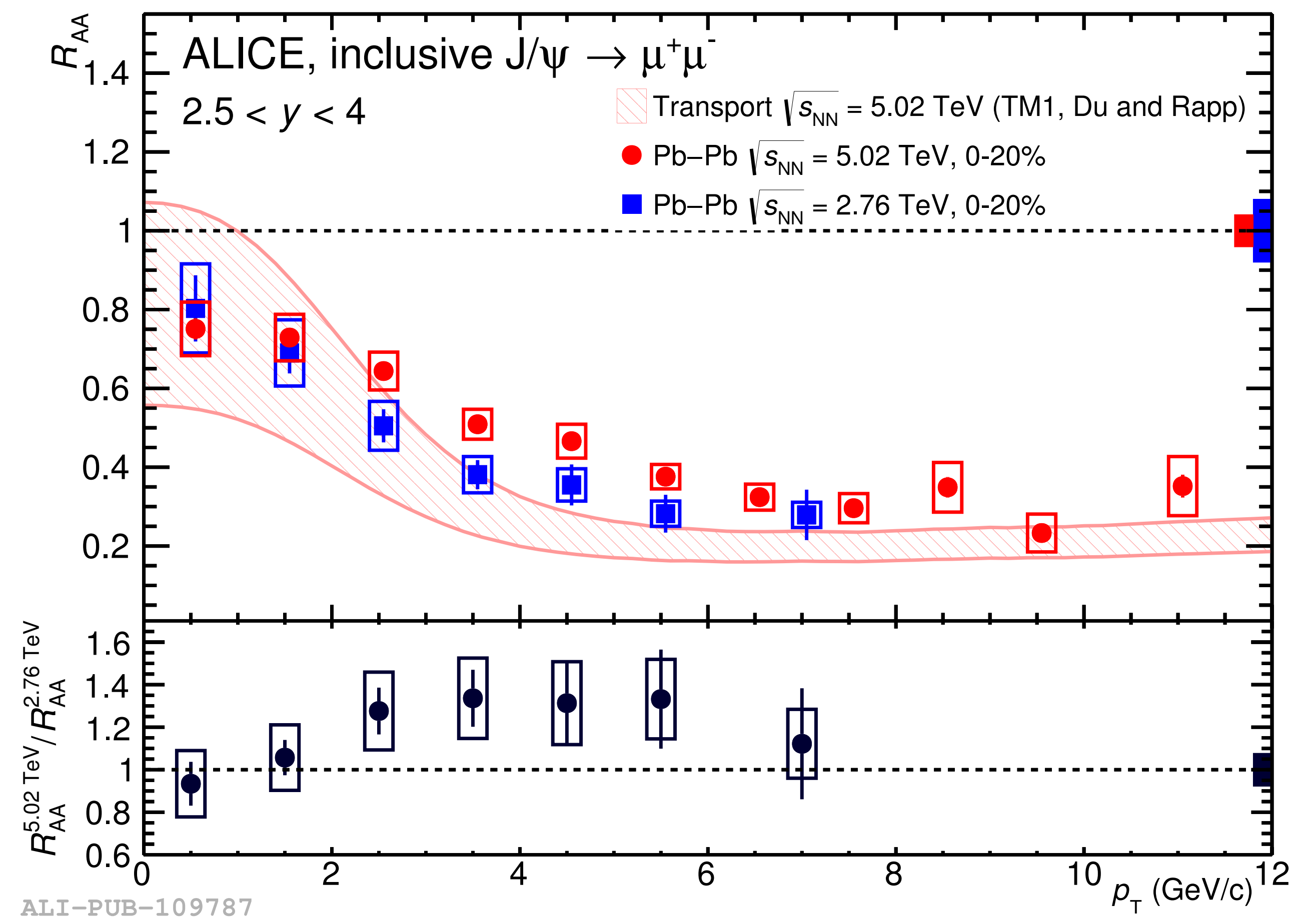

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