TALLER DE ALTAS ENERGÍAS 2011
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Heavy-Ion Collisions (II)

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Contents:

1. Basic ideas about high-p_T particle and heavy flavor production.

2. Radiative energy loss.

3. DIS on nuclei.

4. Linear and non-linear evolution equations: saturation; the CGC.

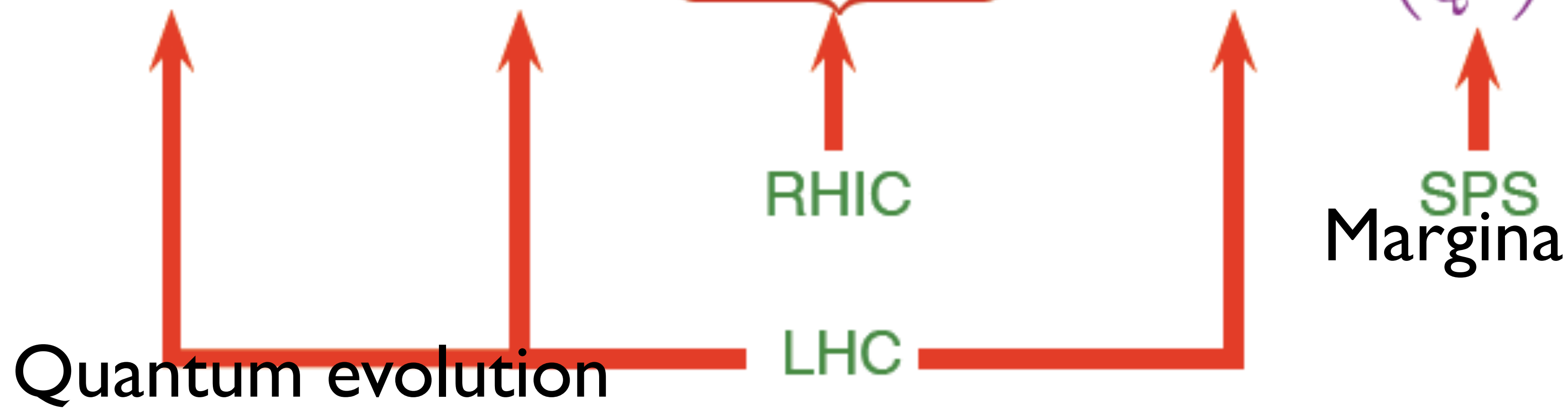
5. Heavy-ion collisions at the LHC.

See Ellis, Stirling, Webber, *QCD and Collider Physics*, Cambridge, 2003; Casaderrey-Solana, Salgado, arXiv:0712.3443 [hep-ph] and refs. therein; NA, hep-ph/0604108 and refs. therein; Roberts, *The structure of the proton*, Cambridge; contributions to *QCD perspectives on Hot and Dense Matter*, Kluwer.

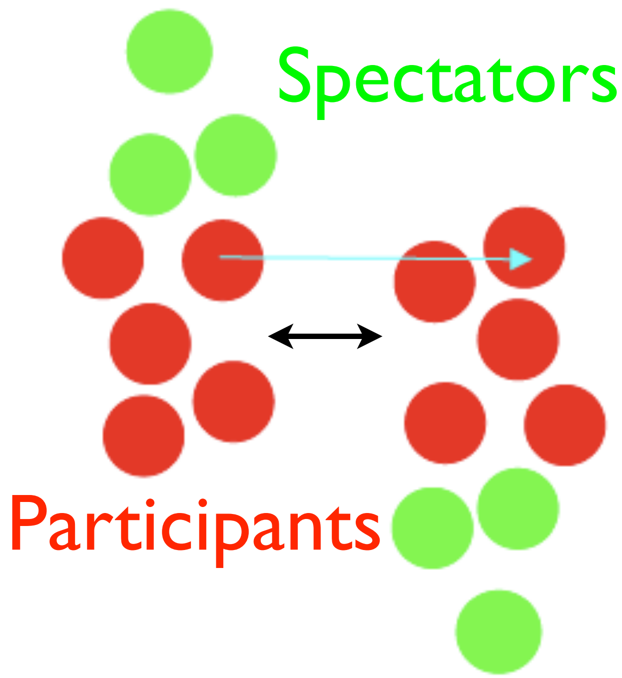
Factorization:

- The usual tool to compute particle production is collinear factorization (for $Q \sim E_{cm} \gg \Lambda_{QCD}$):

$$\sigma^{pp\to h} = f_p(x_1,Q^2) \otimes f_p(x_2,Q^2) \otimes \sigma(x_1,x_2,Q^2) \otimes D(z,Q^2) + \left(\frac{1}{Q^2}\right)^n$$



- Nuclear corrections - no medium, QGP or not - to parton densities and fragmentation functions poorly known.

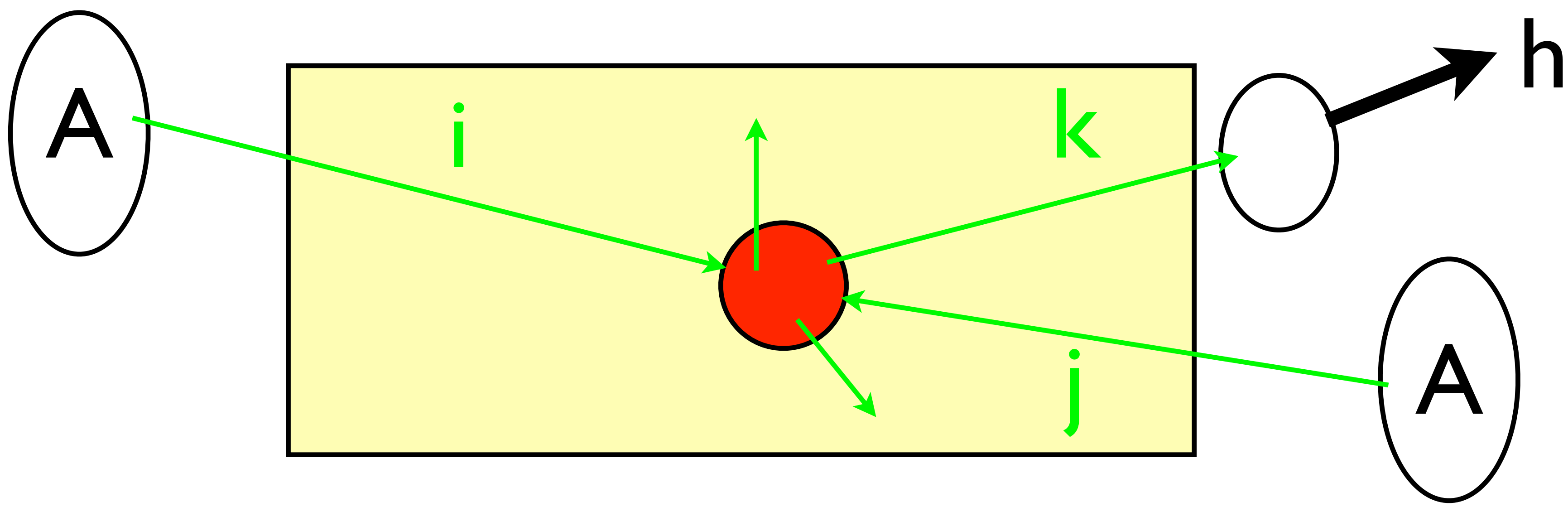


- Nuclear effects usually discussed through the ratio measured/expected: nuclear modification factor, =1 in absence of nuclear effects.

$$R^k_{AB}(y,p_T) = \frac{\frac{dN^k_{AB}}{dy\,dp_T}}{\langle N_{coll}\rangle \frac{dN^k_{pp}}{dy\,dp_T}}$$

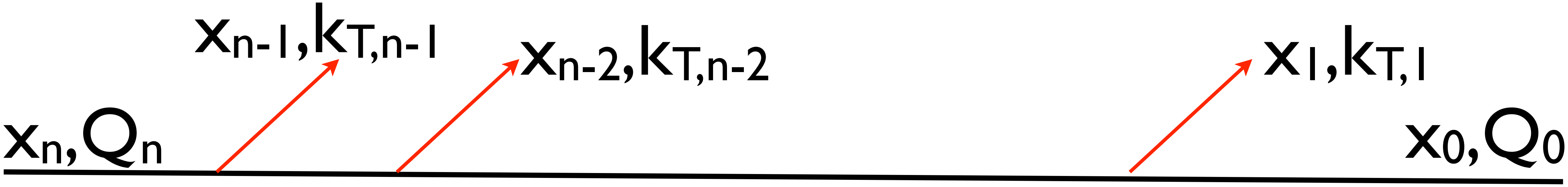
Factorization: 1-particle

$$\frac{d\sigma^{AA\to h}}{dp_T dy} = \int \frac{dx_2}{x_2}\frac{dz}{z}\sum_{i,j} x_1 f_i^A(x_1,Q^2) x_2 f_j^A(x_2,Q^2)\frac{d\hat{\sigma}^{ij\to k}}{d\hat{t}} D_{k\to h}(z,\mu_F^2)$$



- x_i: momentum fraction of hadron N (in A) taken by parton i.
- z: momentum fraction of parton i taken by hadron h.
- Scales: Q, μ_F for factorization, μ_R for renormalization.
- f's and D's evolved according to DGLAP.
- DGLAP evolution and partonic σ computed at NLO (order α_s^2,...) for all observables of interest (h, H, γ, DY, jets).
- Need of resummation of large logs (e.g. log(M_Q/p_T)).

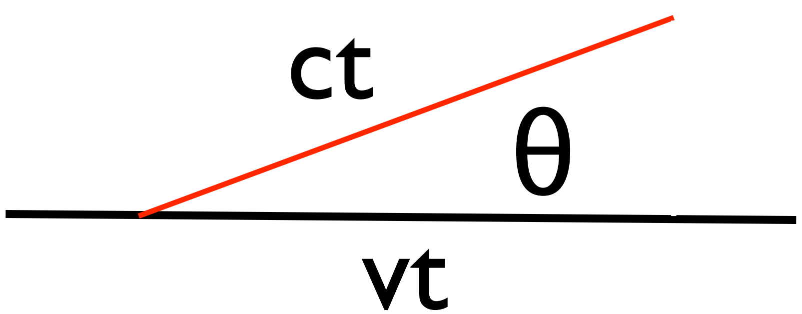
Radiation: dead cone, ang. ordering



$$dP_i = \frac{dx_i}{x_i}\frac{dk_{T,i}^2}{k_{T,i}^2}, \quad \omega_i = x_i E, \quad \theta_i^2 \simeq \frac{k_{T,i}^2}{\omega_i^2}$$

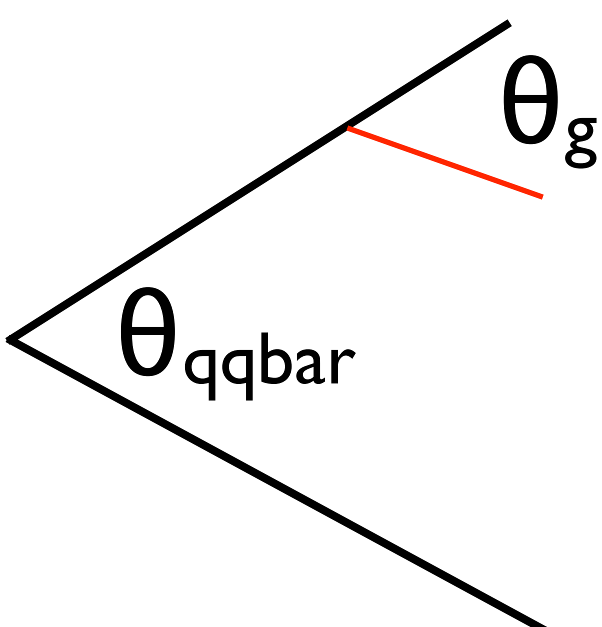
$$Q_n^2 \gg k_{T,n-1}^2 \gg k_{T,n-2}^2 \gg \ldots \gg k_{T,1}^2 \gg Q_0^2$$

$$x_n \ll x_{n-1} \ll x_{n-2} \ll \ldots \ll x_1 \ll x_0$$



$$vt \simeq ct(1-\theta_0^2) \Rightarrow \theta_0^2 = m^2/E^2, \quad \theta^2 \to \theta^2 + \theta_0^2$$

Infrared (soft) and collinear (mass) divergencies.



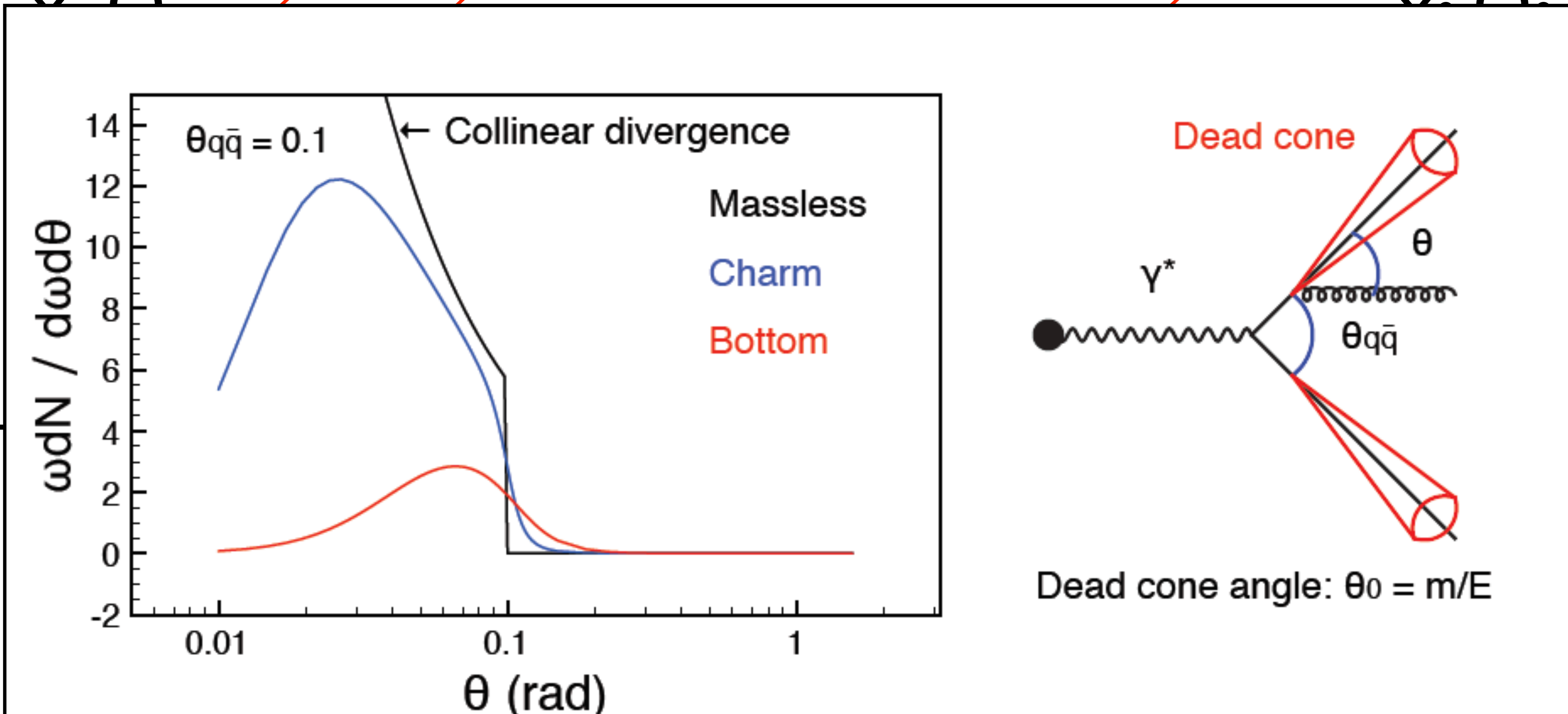
Angular ordering: |qqbarg> → |qqbar>+|g>

$$D_{q\bar{q}} = \theta_{q\bar{q}} t_{coh}, \quad t_{coh} \sim \omega/k_T^2, \quad D_g \sim 1/k_T$$

$$D_{q\bar{q}} = \frac{\theta_{q\bar{q}}}{k_T \theta_g} > D_g \Rightarrow \theta_g < \theta_{q\bar{q}}$$

Radiation: dead cone, ang. ordering

$x_{n-1}, k_{T,n-1}$ $x_{n-2}, k_{T,n-2}$ $x_1, k_{T,1}$



θ_{qqbar}

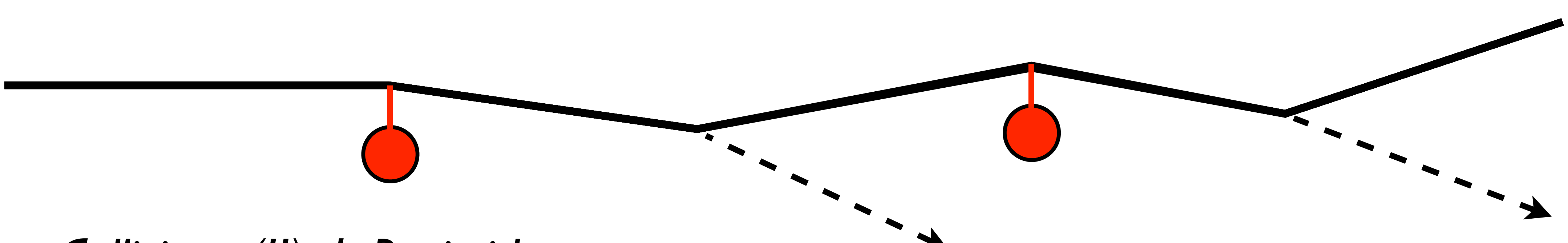
$$D_{q\bar{q}} = \frac{\theta_{q\bar{q}}}{k_T \theta_g} > D_g \Rightarrow \theta_g < \theta_{q\bar{q}}$$

Medium effects:

- Collinear factorization (for $Q \sim E_{cm} >> \Lambda_{QCD}$) is assumed to hold in the medium, with nuclear pdf's evolved using DGLAP and medium-modified fragmentation functions:

$$D_{i\to h}^{med}(x,Q^2)=\int_0^1 \frac{d\epsilon}{1-\epsilon}\,P(\epsilon)\,D_{i\to h}^{vac}\left(\frac{x}{1-\epsilon},Q^2\right)$$

- Fragmentation like in vacuum: outside the medium which should be true for large energies (or p_T for η=0).
- $P(\varepsilon)$: probability to lose some energy (quenching weights) by any kind of energy loss mechanism, either collisional through multiple collisions, or radiative through multiple gluon emission. The latter is suppose to be the dominant phenomenon at large energies.



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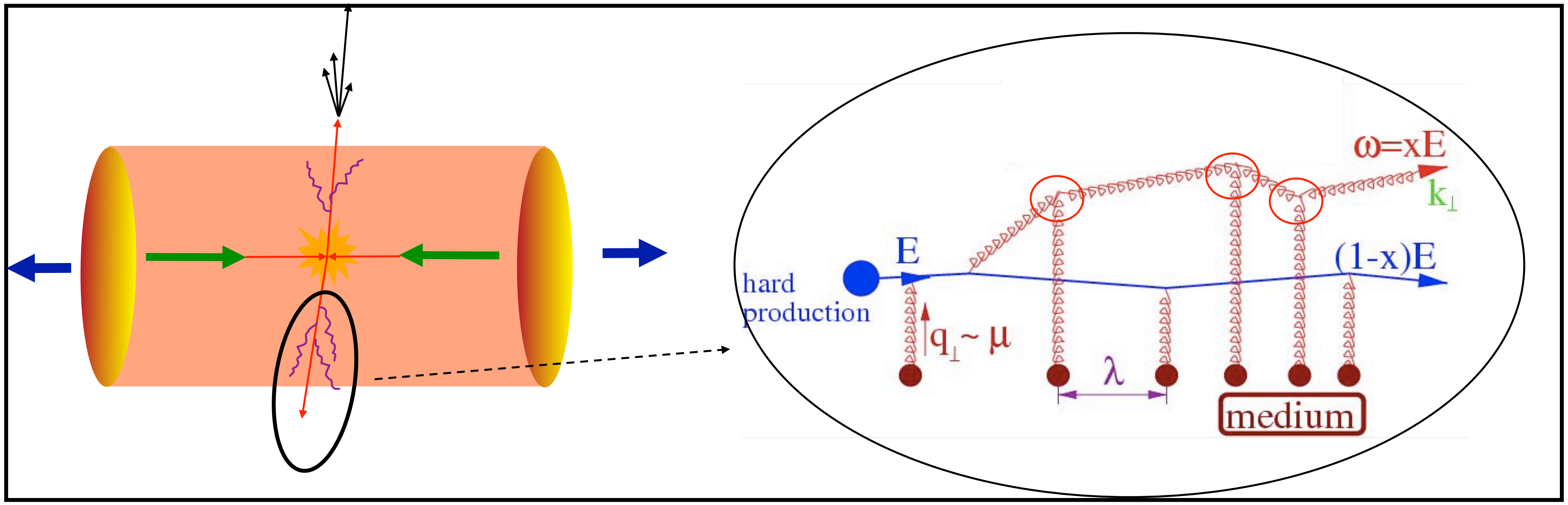
Qualitative arguments:



Consider the de-coherence process |qg> → |q>+|g> **(P1)** and define the transport coefficient qhat=μ^2/λ.

$$\phi = \frac{k_T^2}{2\omega}\Delta z \sim 1 \Rightarrow \omega, k_T^2 \ll 1 \ \text{ suppressed} \qquad \phi \sim \frac{\hat{q}L}{2\omega}L = \frac{\omega_c}{\omega} \sim 1 \Rightarrow \omega > \omega_c \ \text{ suppressed}$$

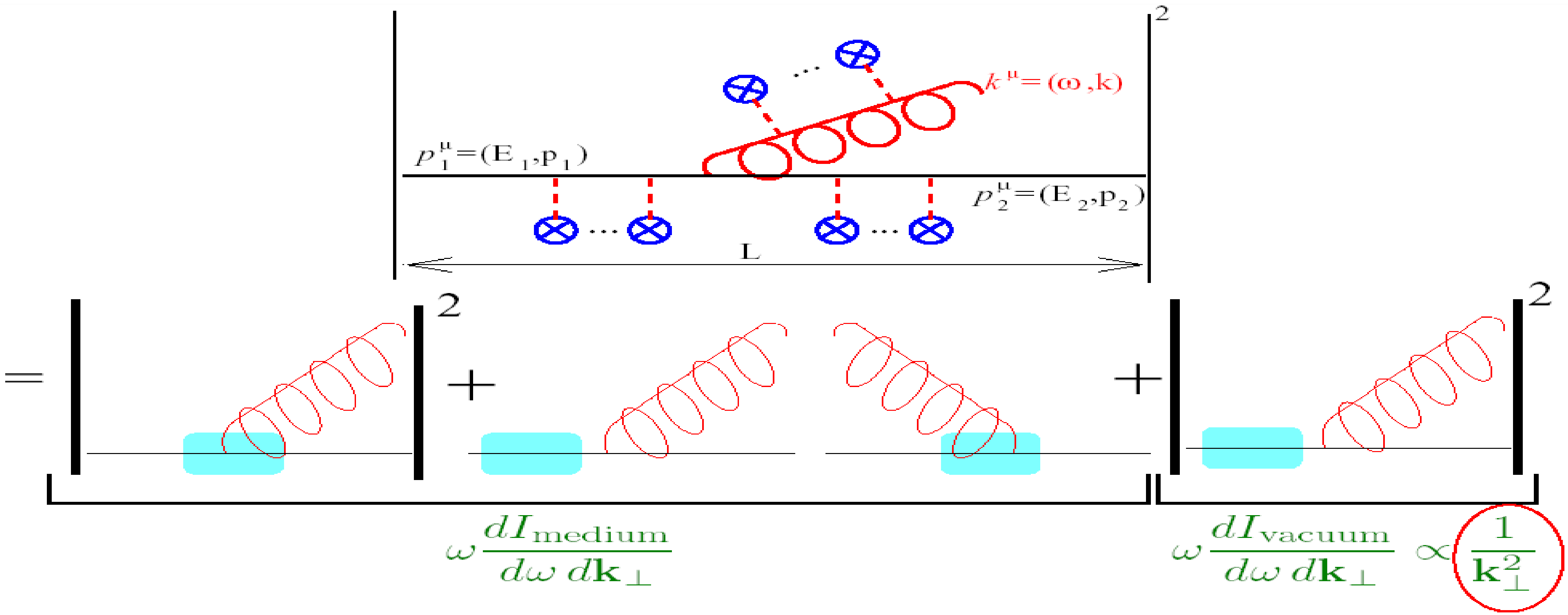
⇒ IRC safe!!!!

$$\hat{q}t_{coh} \simeq \frac{\hat{q}\omega}{\langle k_T^2\rangle} \simeq \langle k_T^2\rangle, \quad \langle k_T^2\rangle \simeq \sqrt{\hat{q}\omega}$$

$$-\frac{dE}{dz} = \int d\omega \, \frac{1}{t_{coh}} \, \omega \, \frac{dI}{d\omega}\bigg|_{1 \ scat} \simeq \alpha_s C_R \int^{\omega_c} d\omega \sqrt{\frac{\hat{q}}{\omega}} \Rightarrow -\Delta E \propto \alpha_s C_R \hat{q} L^2$$

Models:

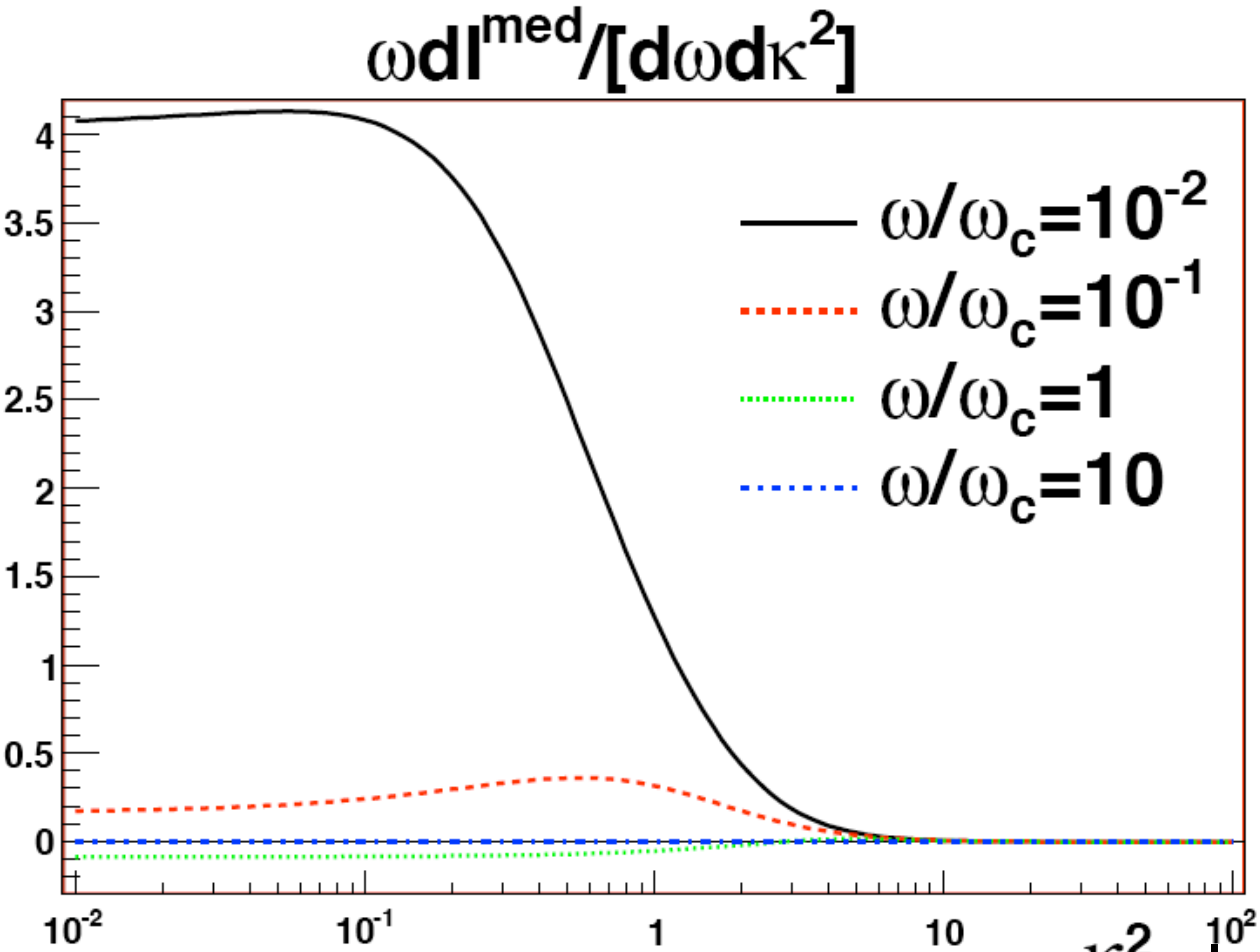
Medium-modified gluon radiation through interference of production and rescattering.



Two parameters define the medium: one characterizing the density and strength of interactions with the medium, plus the length (geometry, dynamical expansion).

Models:

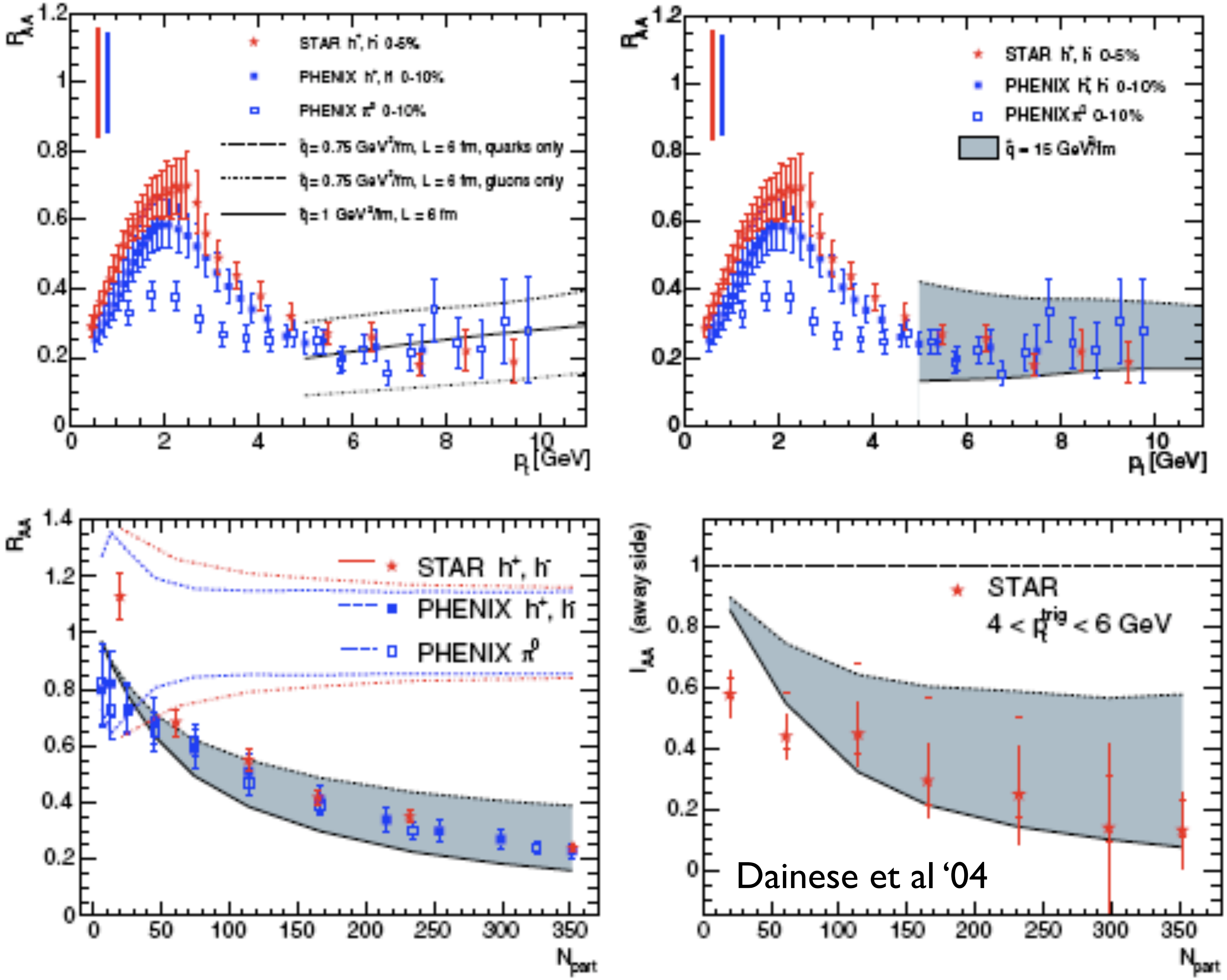
Me ... on
an ...



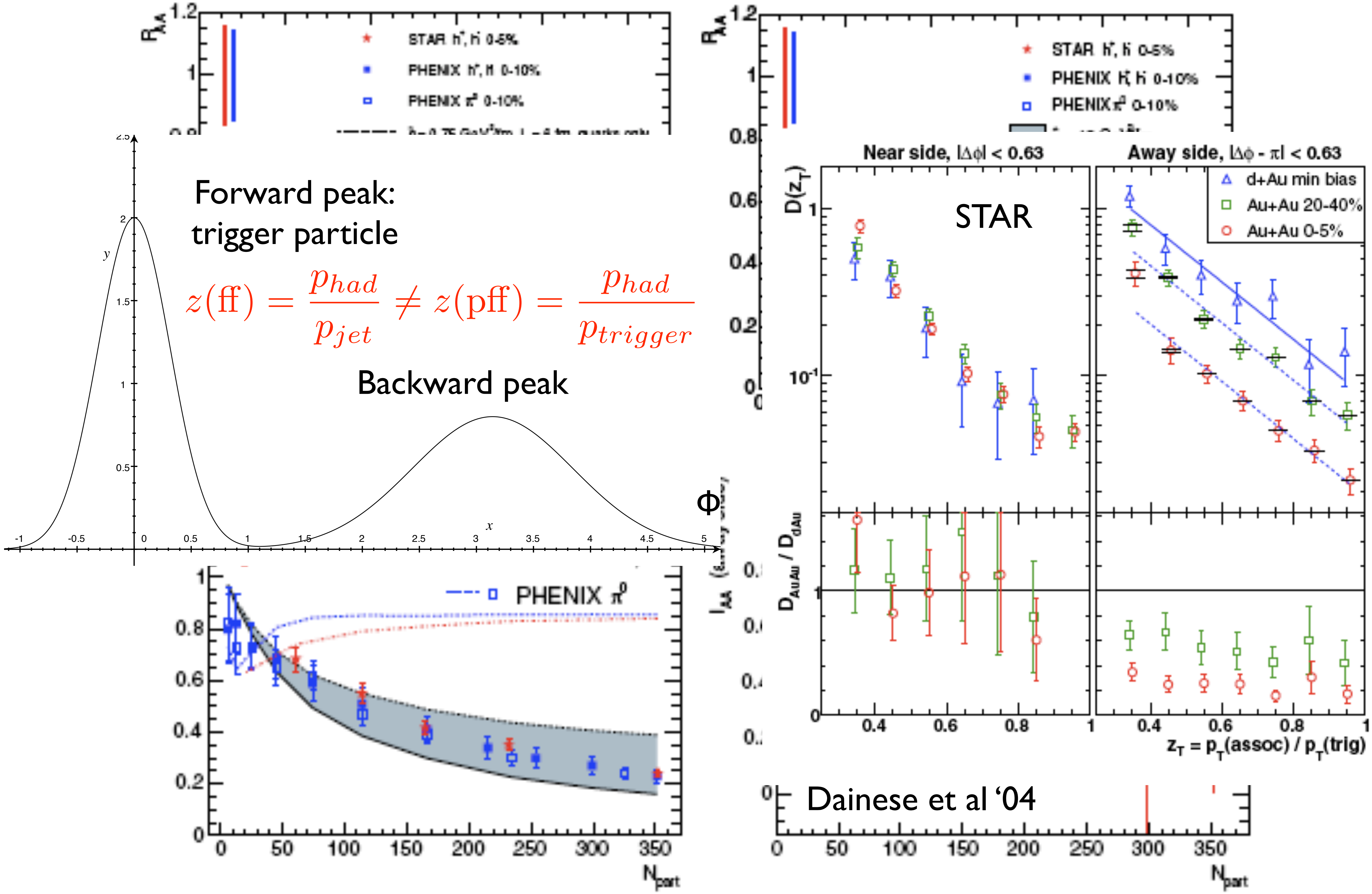
$\kappa^2 = k_T^2/(\text{qhatL})$

Tv ...
an ...
(g ...

Radiative eloss: light hadrons (I)



Radiative eloss: light hadrons (I)

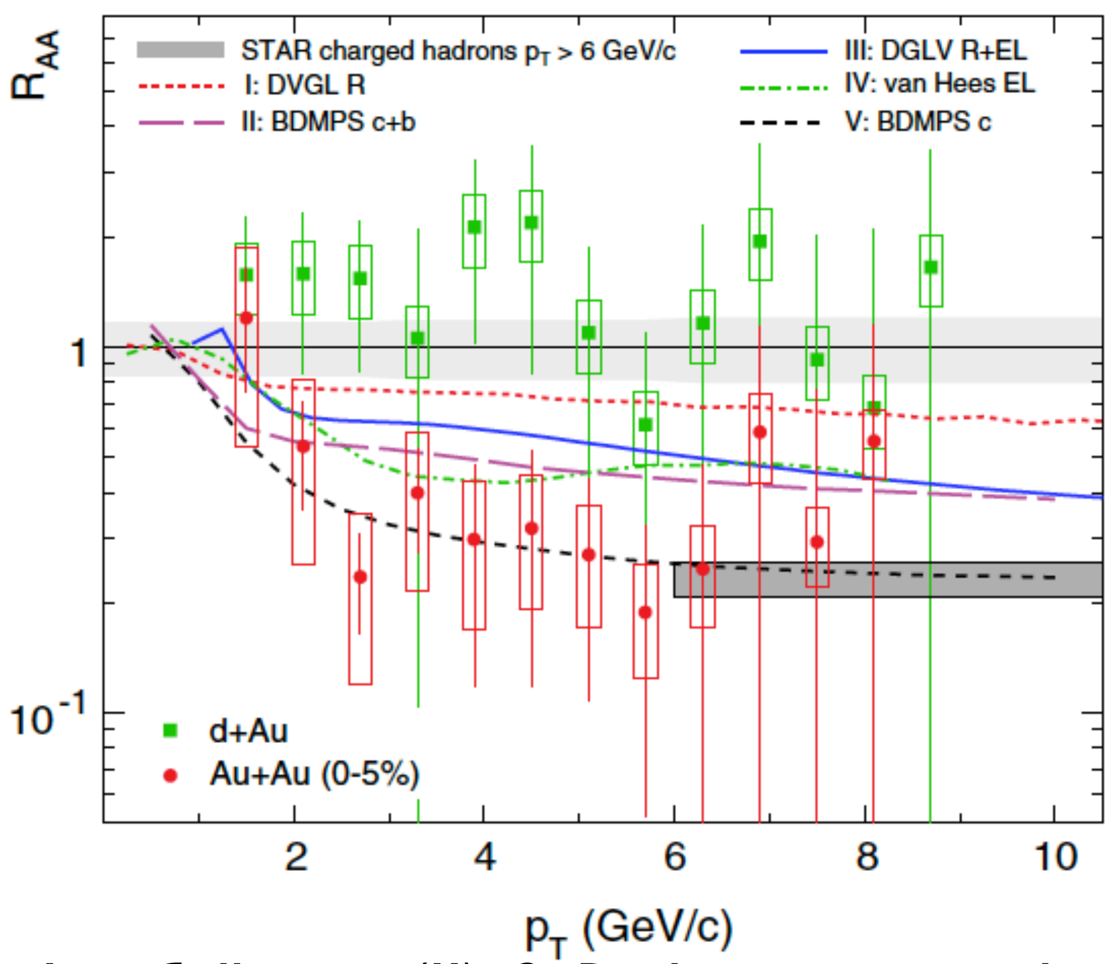


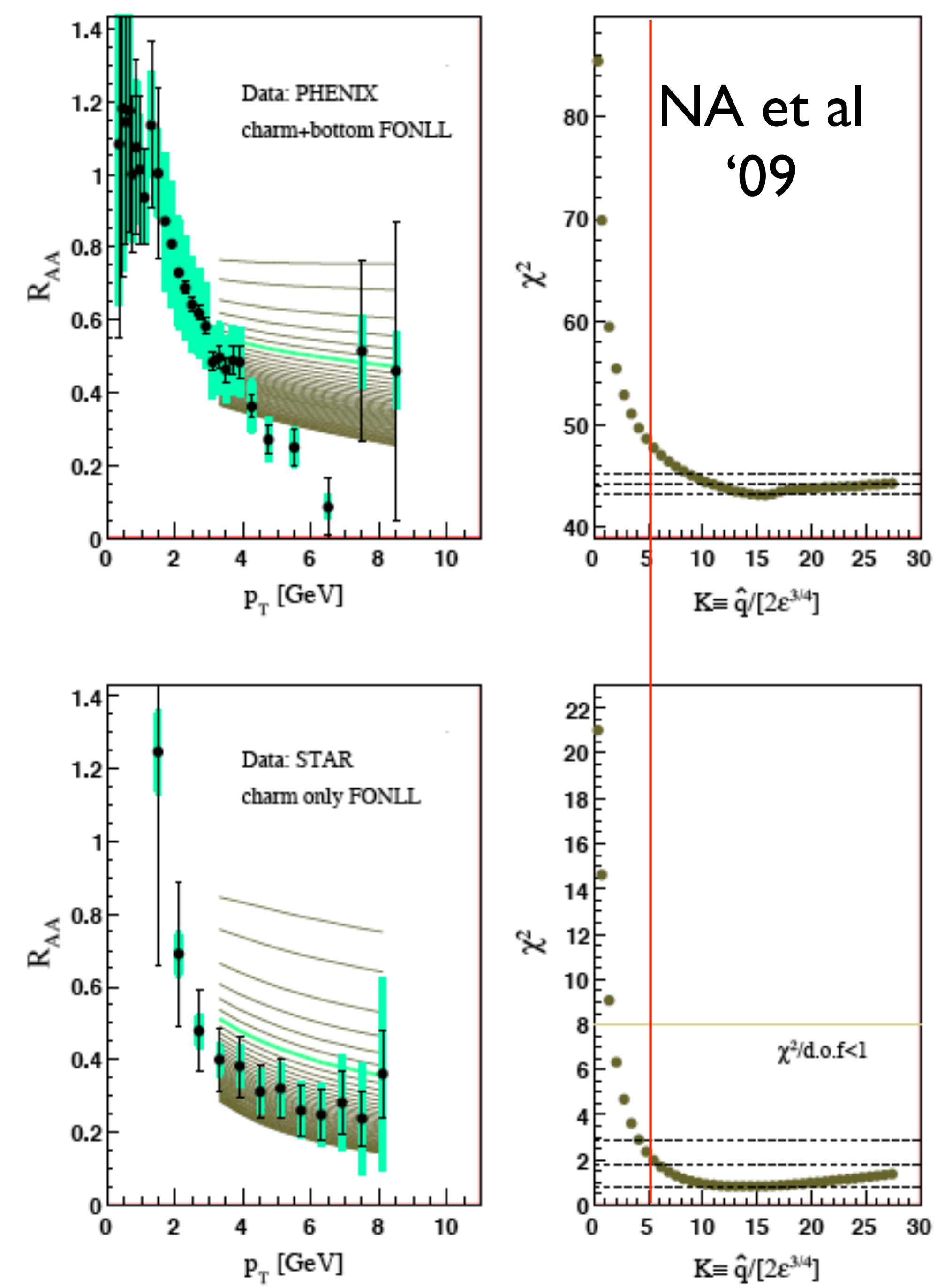
Radiative eloss: non-photonic e's

- Prediction from radiative energy loss: **ΔE(g)>ΔE(q)>ΔE(Q)**.

- Non-photonic electrons not conclusive: benchmark, hadronization, collisional, resonances dynamical medium ...

- Very difficult observable: disentangle c, b, heavy mesons,...





Radiative eloss: limitations

• The extracted value of qhat depends on medium model $1<\hat{q}<15$ GeV^2/fm ⇒ interface with realistic medium.

• Calculations done in the high-energy approximation: only soft emissions energy-momentum conservation imposed a posteriori ⇒ Monte Carlo.

• Multiple gluon emission: Quenching Weights independent (Poissonian) gluon emission: assumption! ⇒ Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

• No role of virtuality in medium emissions; medium and vacuum treated differently ⇒ modified DGLAP evolution.

Radiative eloss: limitations

• Th
1<qh

• Ca ... t
emis ... ri ⇒
Mont

• Mu
(Pois ... M,
PYQ

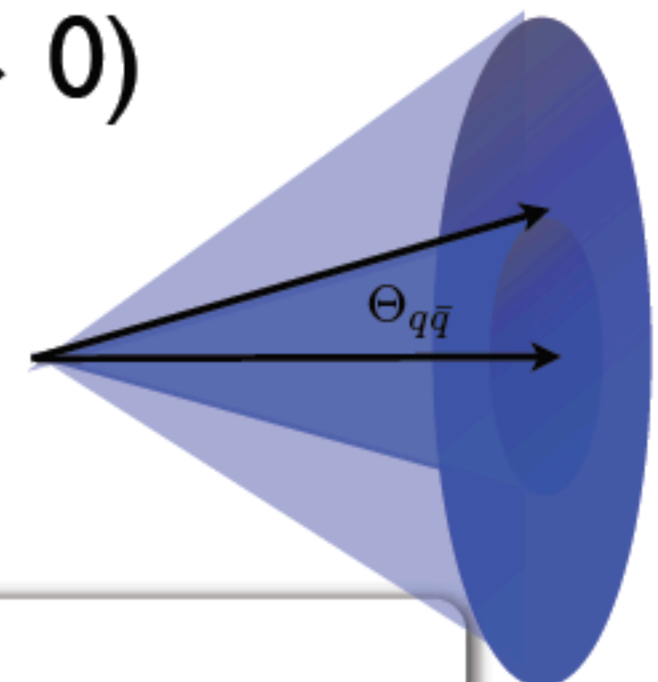
• No ... m
treat

NEW: Mehtar-Tani et al '10-'11

Leading Log (ω→ 0)

$\Delta_{\rm med} \to 0$ (Coherence)

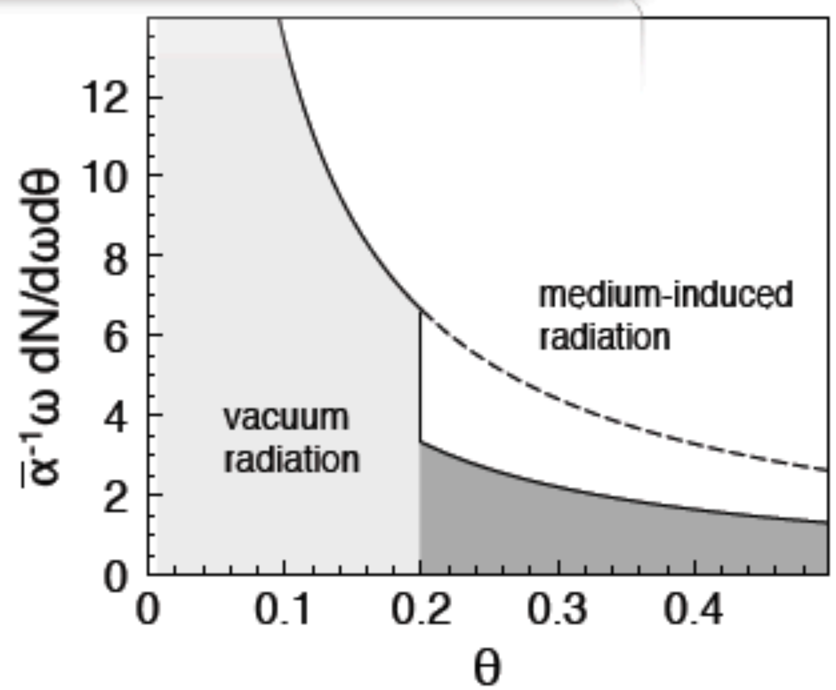
$\Delta_{\rm med} \to 1$ (Decoherence)



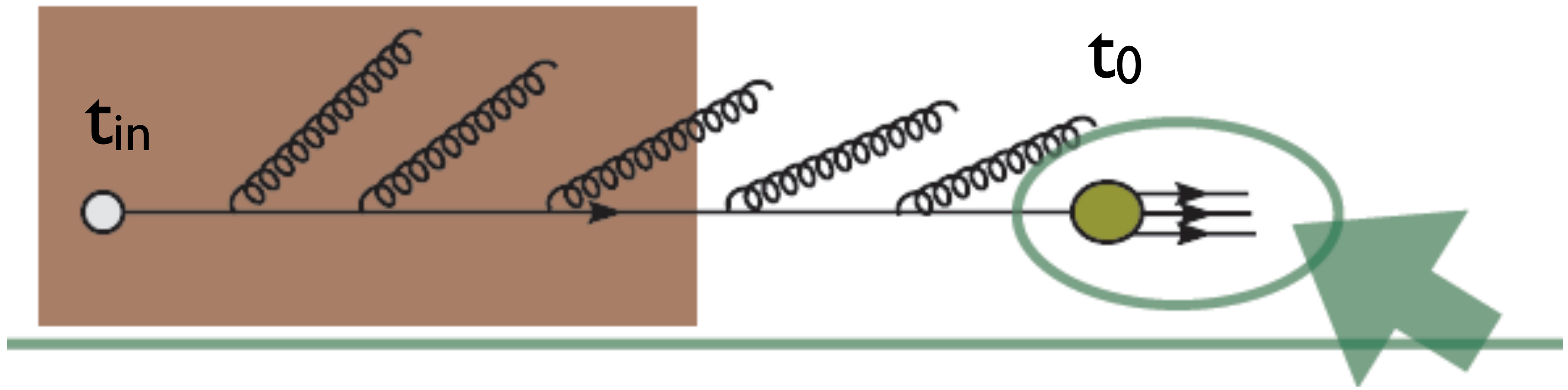
$$dN^{\rm tot}_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\, d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right] .$$

Total decoherence in opaque media

$$dN^{\rm tot}_{q,\gamma^*}\Big|_{\rm opaque} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\, d\theta}{1-\cos\theta} .$$



Monte Carlo (I):



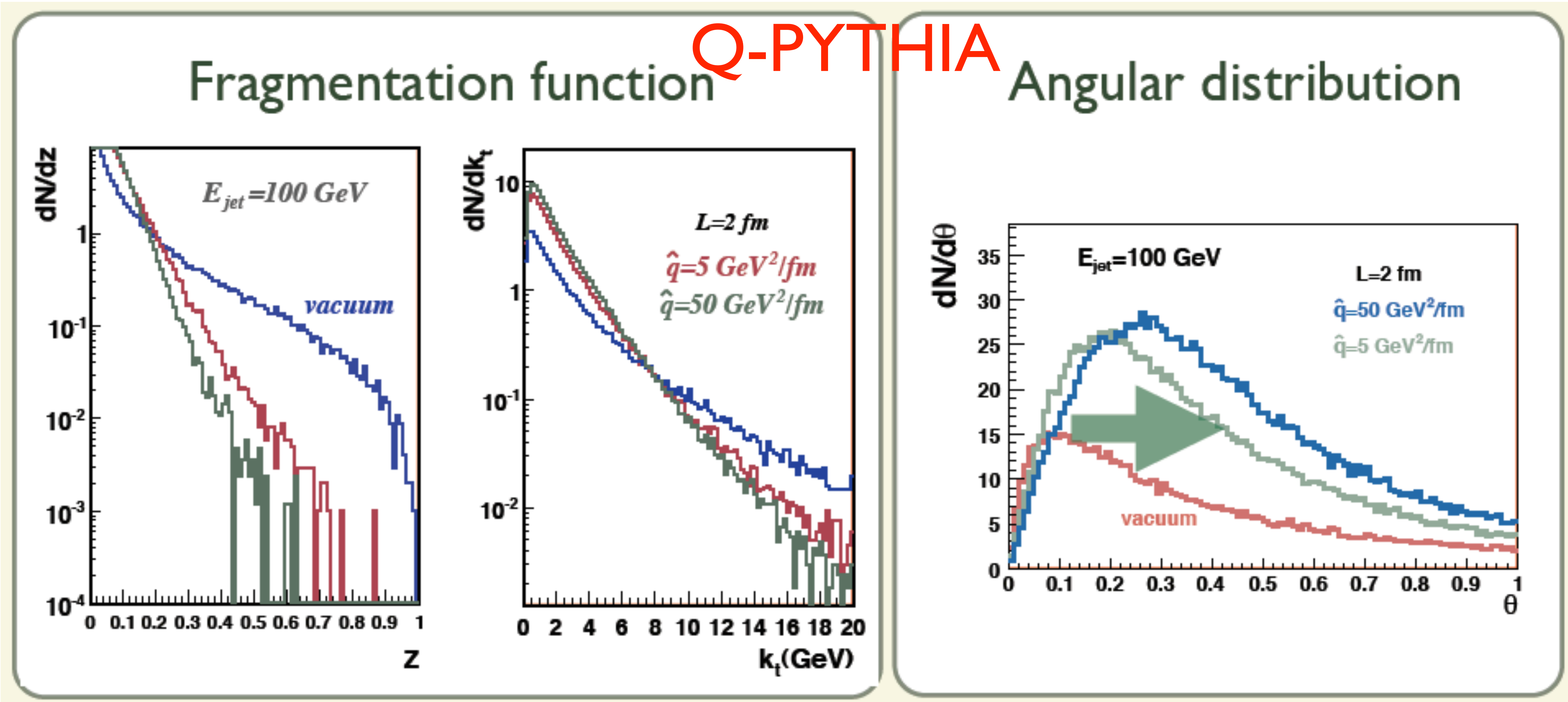
- **Assumption**: hadronization is not affected by the medium: looks OK at RHIC for p_T>7-10 GeV.
- The **splittings are modified:** either radiatively (Q-PYTHIA) or radiative+collisionally (JEWELL, PYQUEN); or the evolution is enlarged due to momentum broadening (YaJEM).

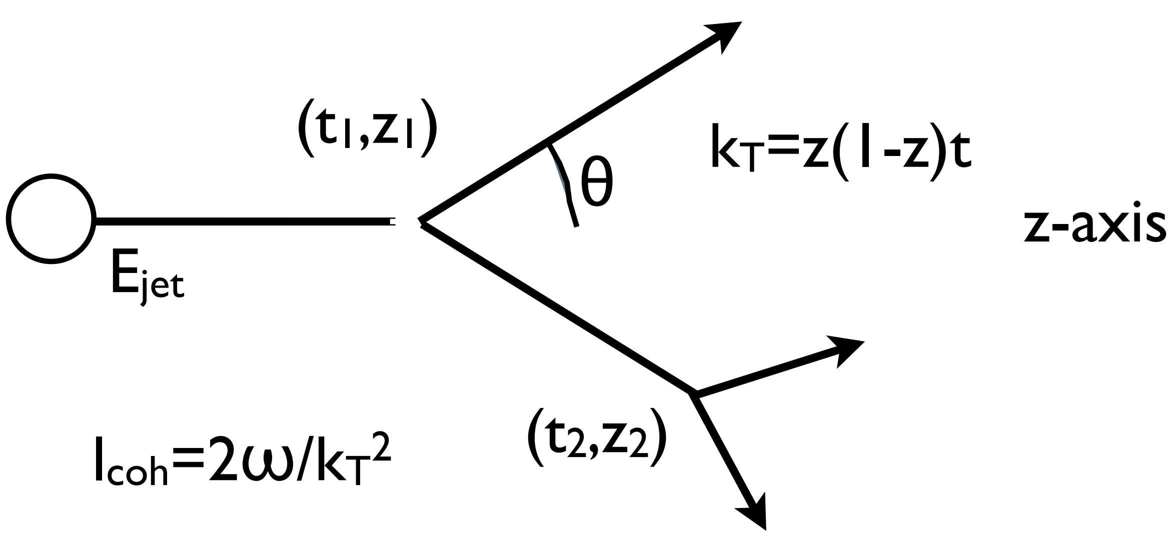
- **Underlying ingredients**: factorization no emission/emission/no emission/... (Sudakov/splitting/Sudakov/...) holds in the medium, and the evolution scale (t,k_T,Θ) can be related with the medium length → both to be proved (Jet Calculus in a medium).

Monte Carlo (II):

- The MC's generically reproduce the expectations:
  - → Particle spectrum softens (jet quenching).
  - → Emission angle enlarges (jet broadening).
  - → Intra-jet multiplicity enlarges.

Monte Carlo (II):





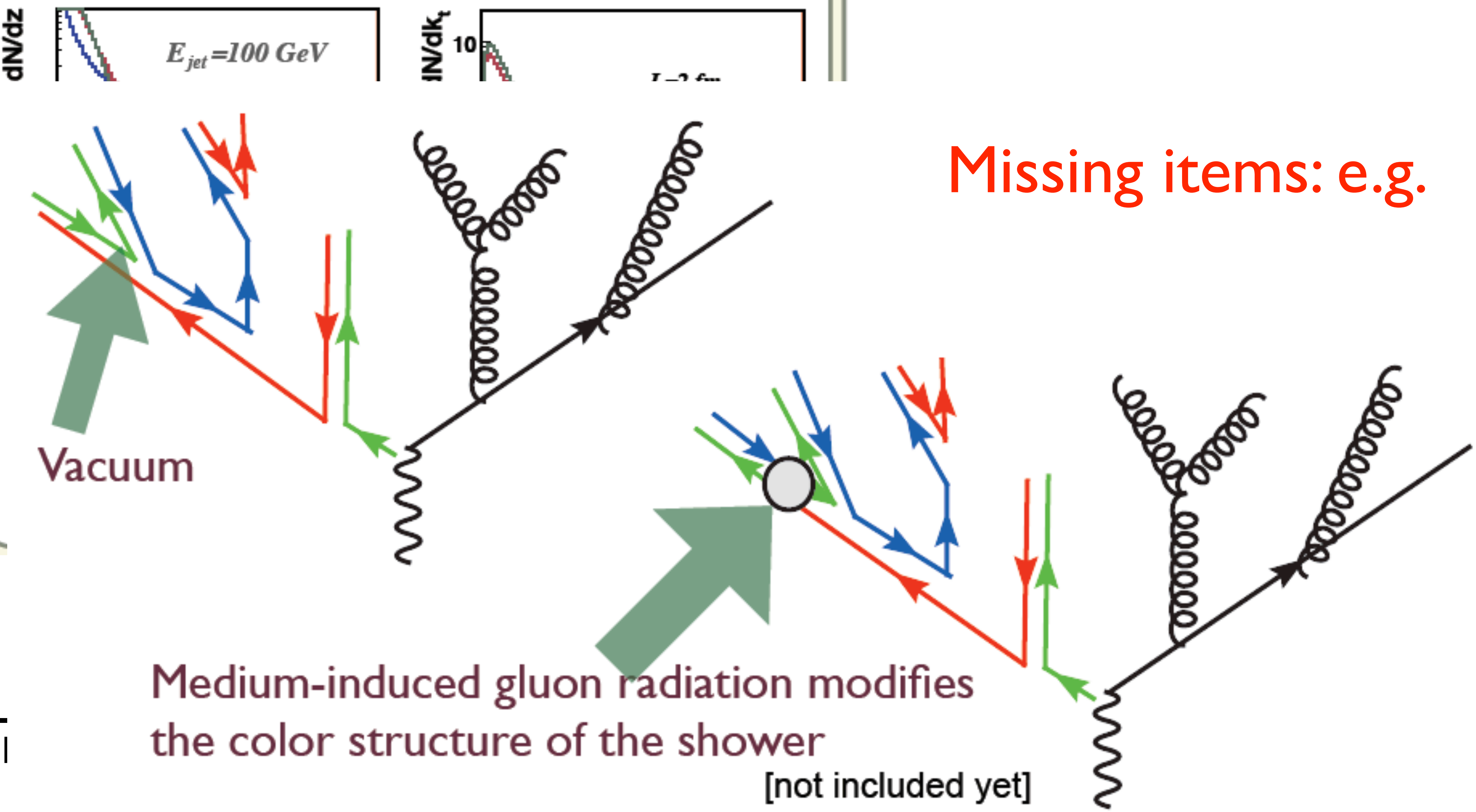
- Intense activity at RHIC and the LHC: jet reconstruction in a large background (small clustering parameters versus out-of-'cone' medium modification).

Monte Carlo (II):

Q-PYTHIA

Fragmentation function

Angular distribution



Missing items: e.g.

parameters versus out-of- cone medium modification).

$l_{coh}=2\omega/k_T^2$

(t_2,z_2)

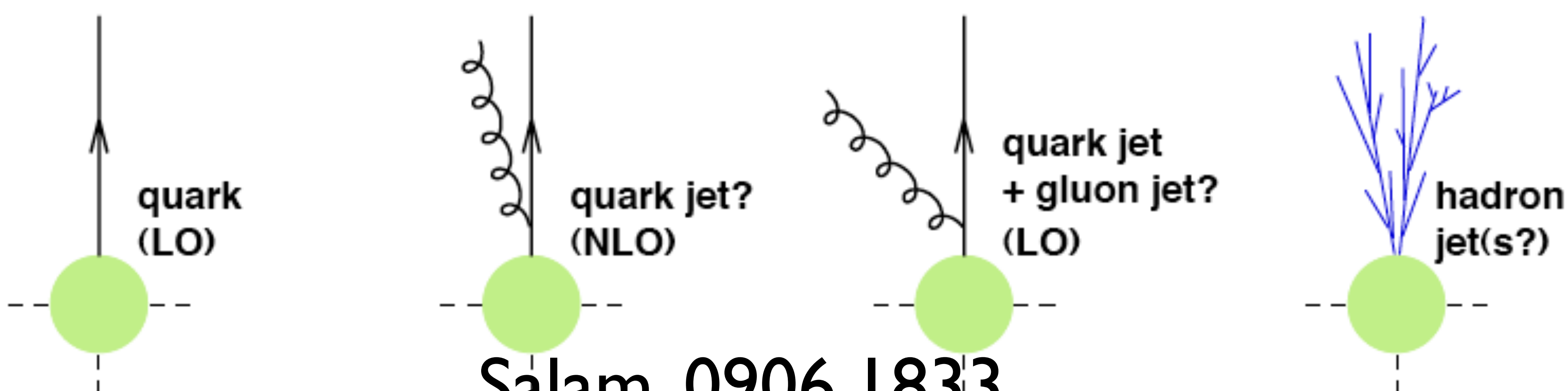
Jets (I):

• Single-particle inclusive distributions suffer from several biases: steep partonic spectrum which enhances small energy losses (trigger bias), geometric bias towards the surface,...

• They come from our inability to reconstruct the energy of the 'parton': we cannot distinguish a low energy, little degraded one from a high energy, highly degraded one.

Jets are the most direct of all hard probes of the medium.

As close as you can get to the original quark or gluon near its time of creation



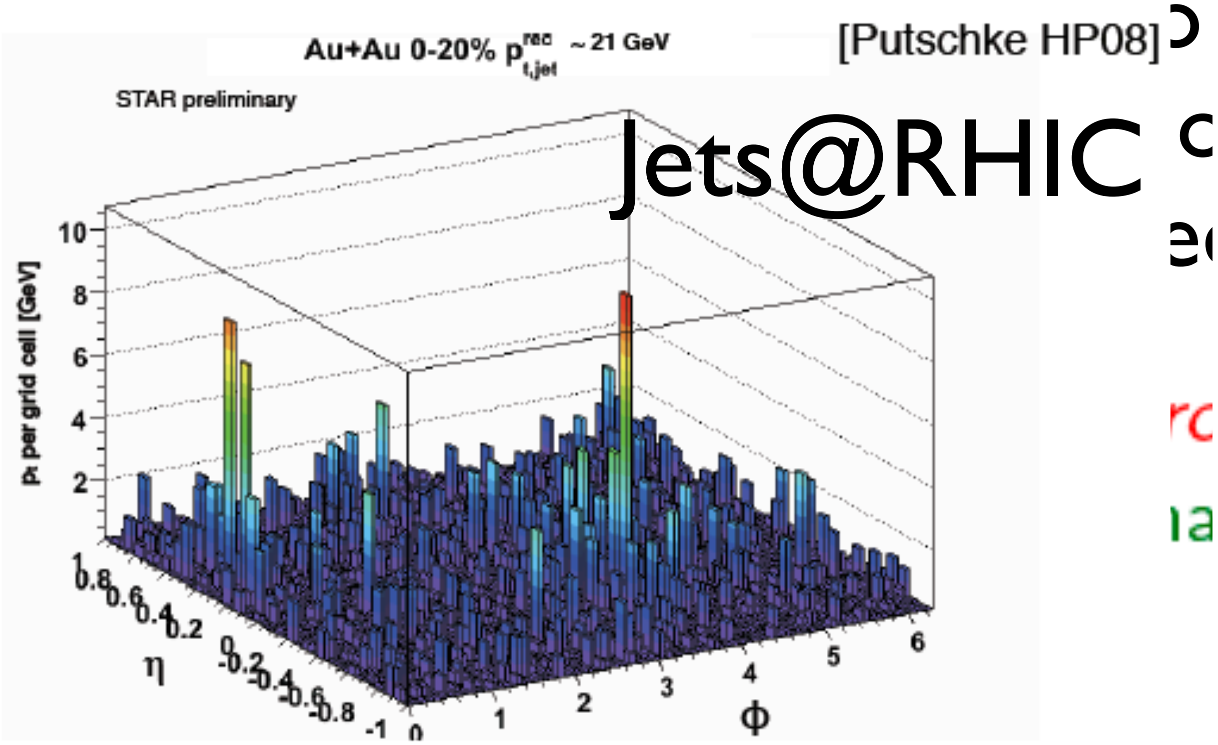
Salam, 0906.1833

• Jets come with a definition: clustering or reconstruction algorithm.

Jets (I):

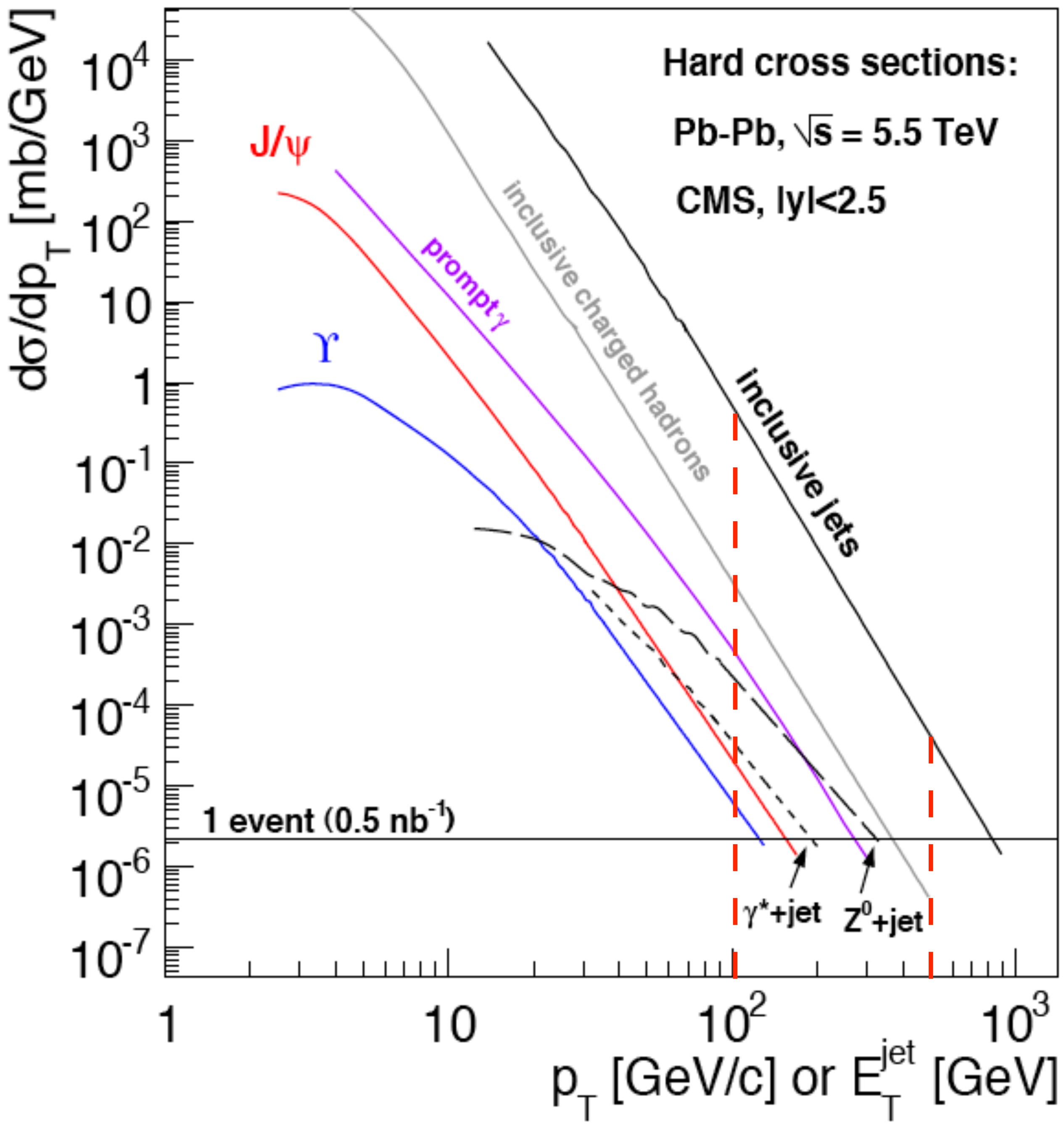
- Single-particle inclusive distribut[...] steep partonic spectrum which en[...] (trigger bias), geometric bias towa[...]

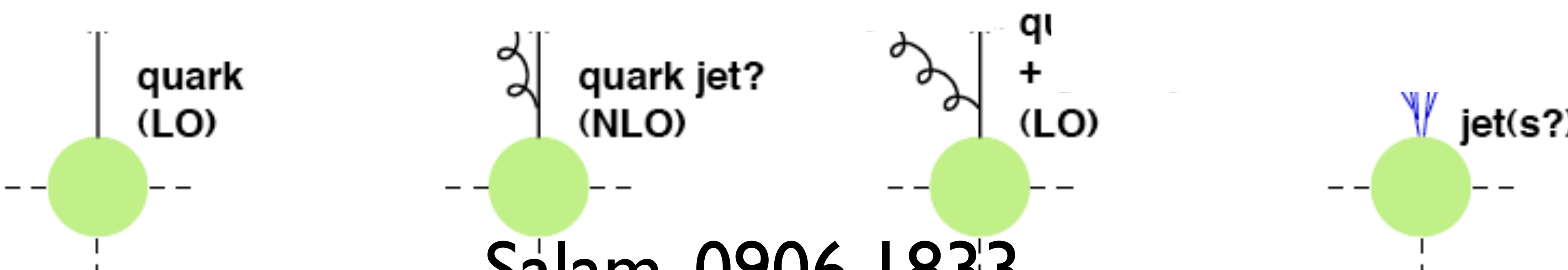
First results appeared in HP2008!



Jets@RHIC

A lot of work still needed



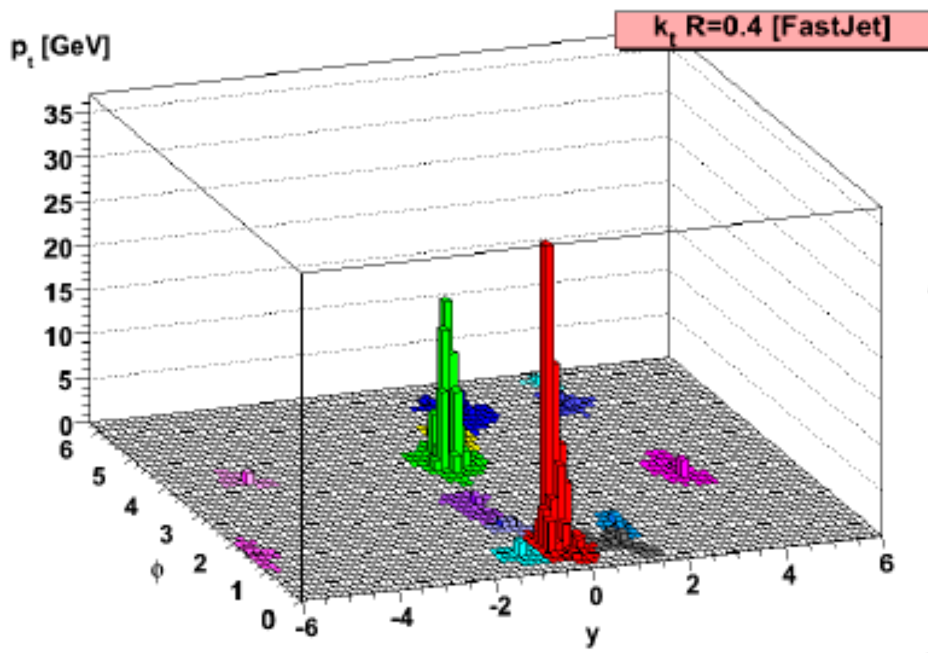


Salam, 0906.1833

clustering or reconstruction algorithm.

Jets (II):

- Techniques for background substraction (the underlying event), designed to deal with the pileup at the LHC, can be applied in HI.
- Note: typically several 100 GeV are deposited per unit in $\eta\times\Phi$.

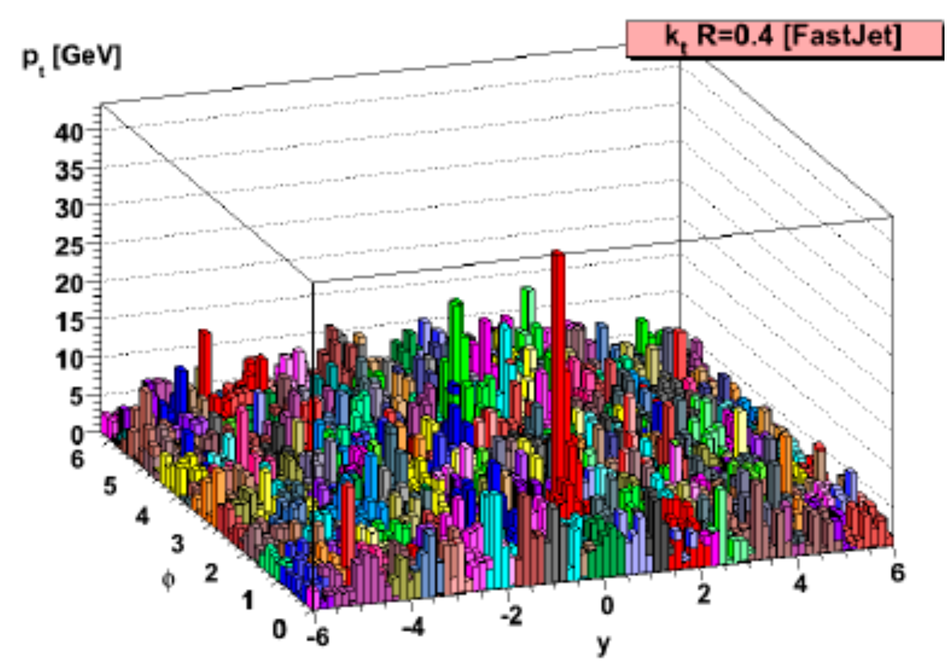


An example hard event

$p_t \sim 100$ GeV
Generated with Pythia

Mixed into LHC HI environment

HydJet, $dN_{ch}/dy \simeq 1600$



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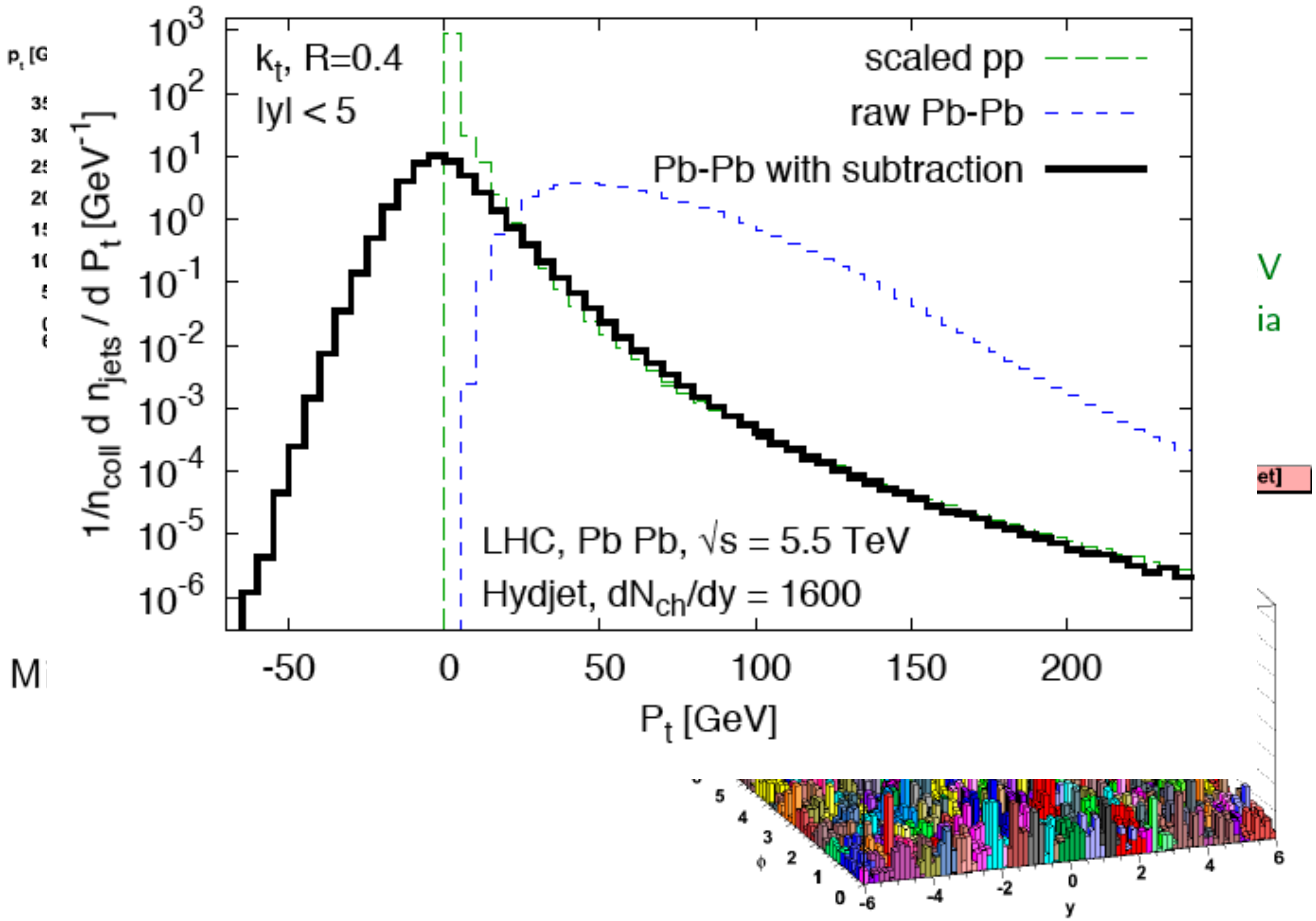

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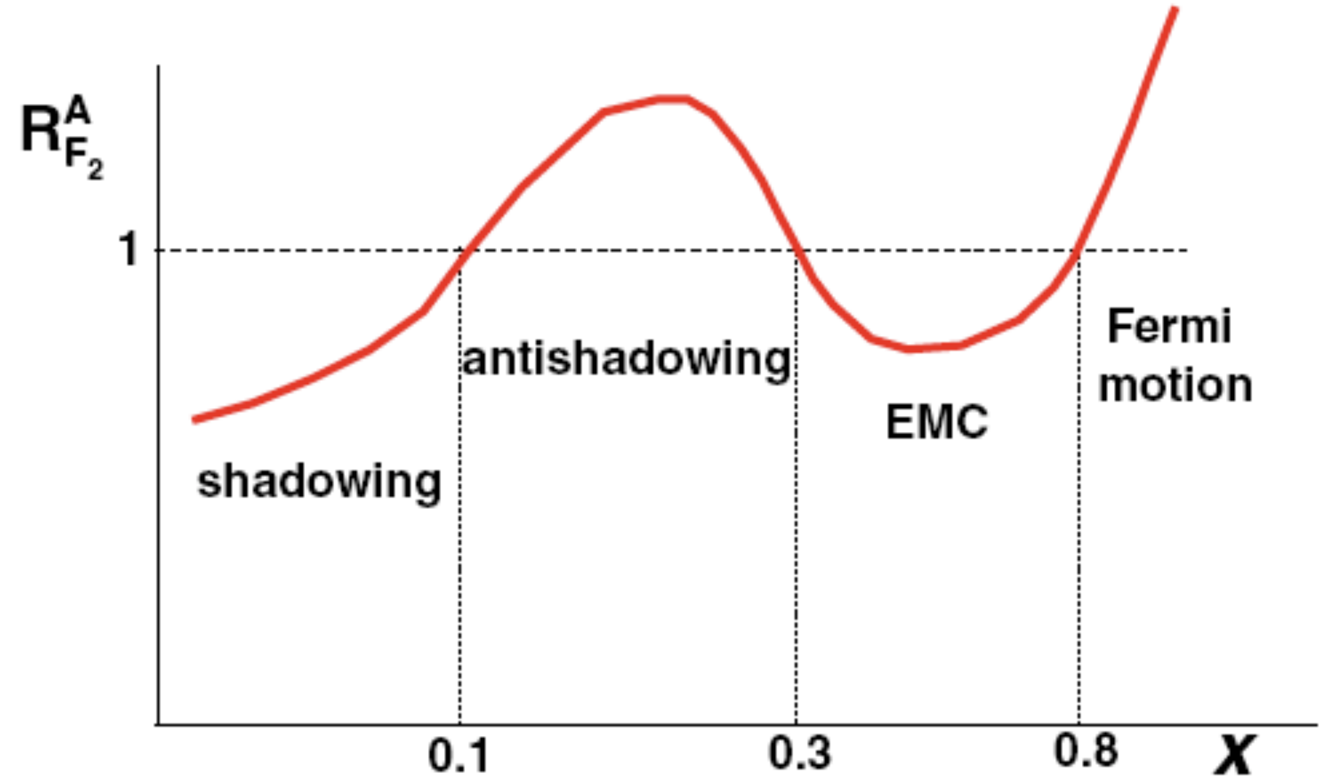
DIS on nuclei:

$$R^A_{F_2}(x, Q^2) = \frac{F_2^A(x, Q^2)}{A F_2^{\text{nucleon}}(x, Q^2)}$$

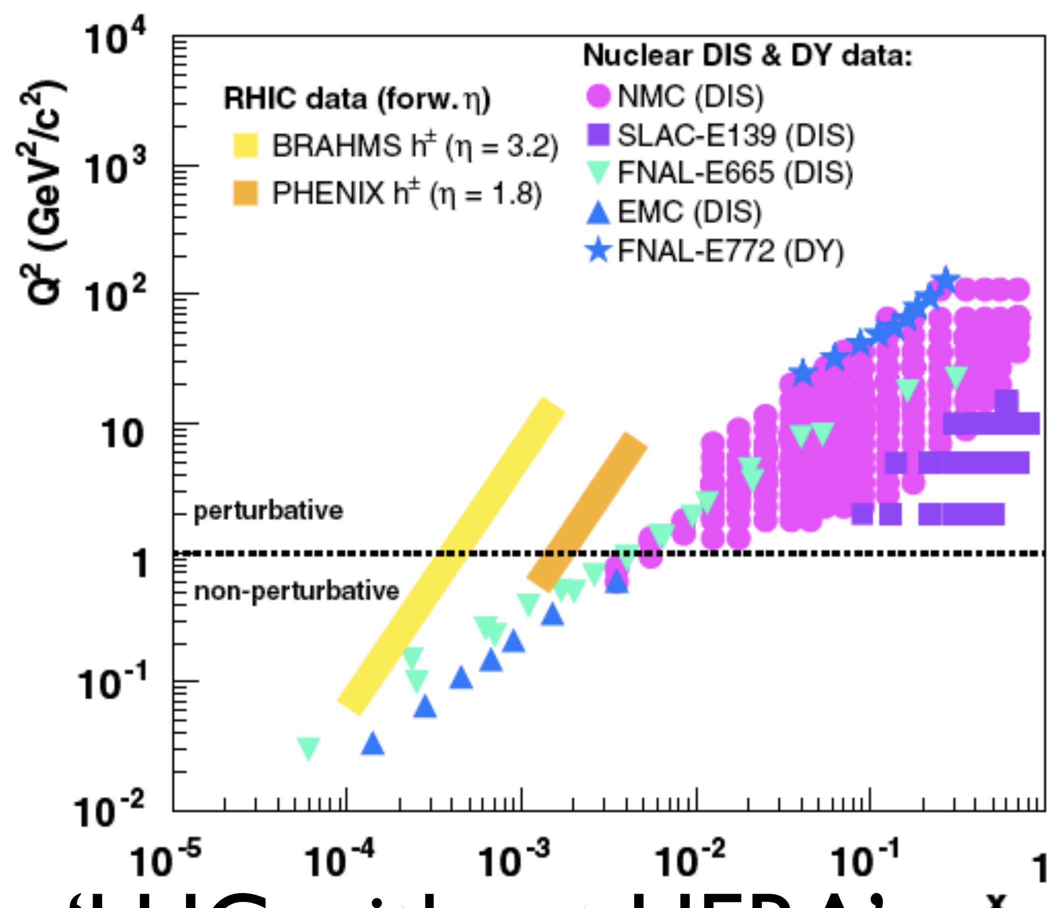


- R=1 indicates the absence of nuclear effects.

- R≠1 discovered in the early 70's.

- Each region demands a different explanation.

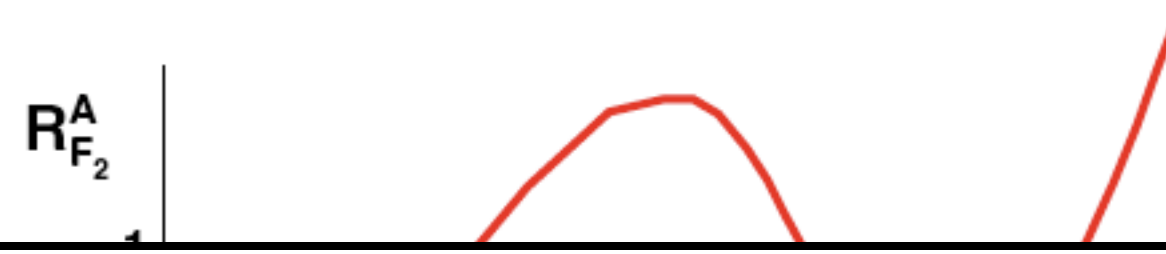
- I will be mostly interested in small x (<0.1) relevant for high energies: isospin effects neglected.

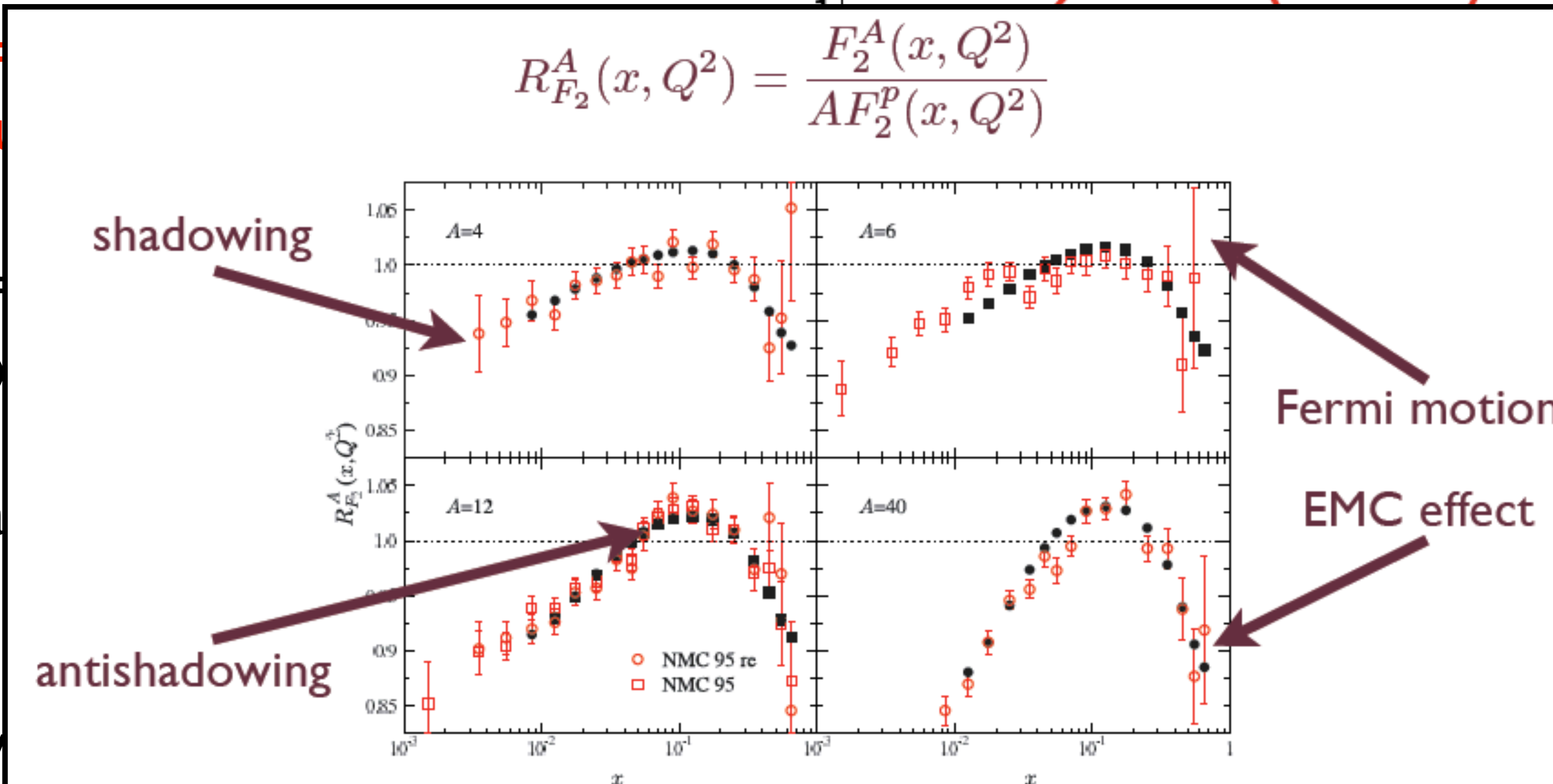


'LHC without HERA'

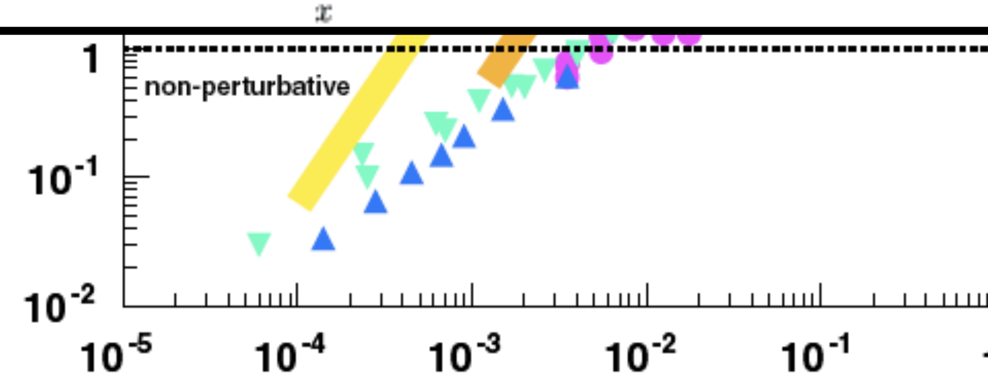
DIS on nuclei:

$$R^A_{F_2}(x,Q^2) = \frac{F_2^A(x,Q^2)}{A F_2^{\text{nucleon}}(x,Q^2)}$$





- R= ... of nu...
- R= ... early...
- Ea... diffe...
- I v... small x (<0.1) relevant for high energies: isospin effects neglected.



‘LHC without HERA’

Global fits:

→ Data in EPS09 (Q^2, M^2>1.69 GeV^2; p_T>1.7 GeV): 92 from DY (E-772 and 886), 20 from π^0 (PHENIX), rest up to 929 from DIS (E-135, EMC, NMC). Neutrino data under discussion.

⇛ Cross sections computed in collinear factorization

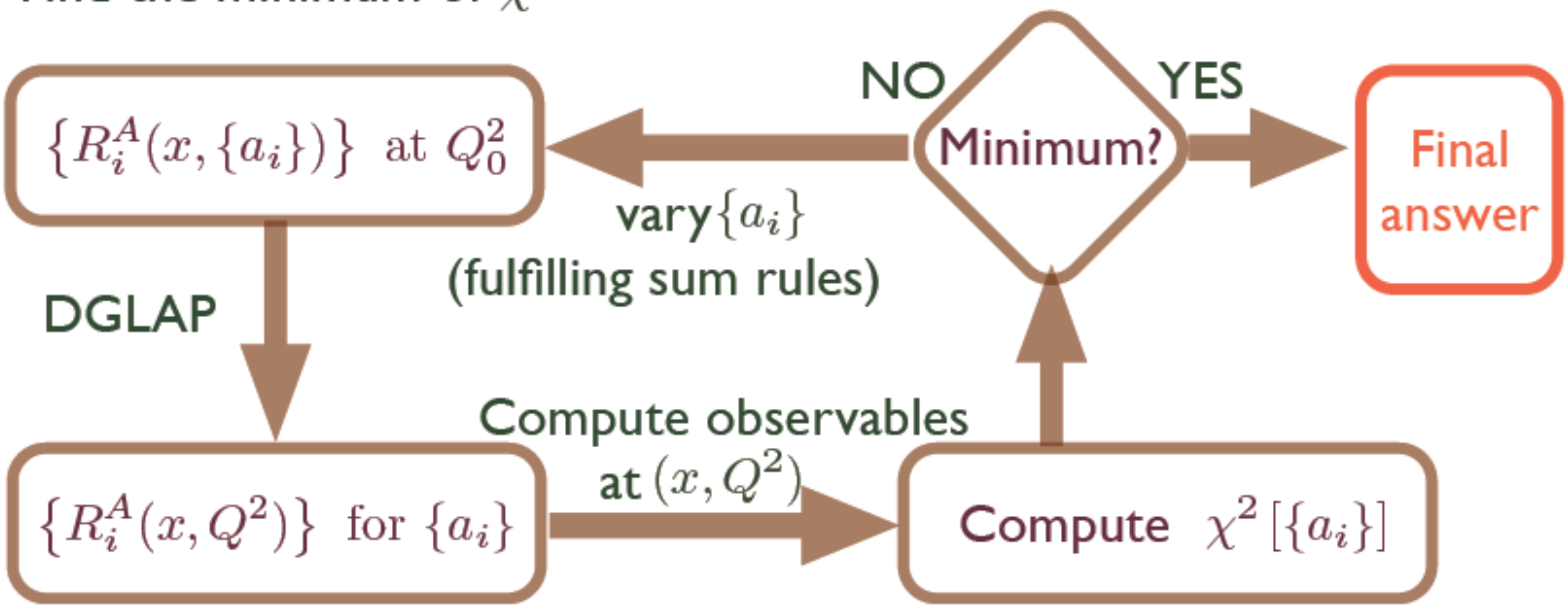
⇛ Define

$$R_i^A(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$

⇛ Using a known set for free protons (CTEQ, MRST....)

⇛ and DGLAP evolution of the nuclear and free proton PDFs

⇛ Find the minimum of χ^2



Global fits:

- → Eskola '94: DGLAP for nuclei.
- → EKS98: first global analysis, LO, DIS+DY.
- → Others non global analysis: Indumathi-Zhu, FGS.
- → nDS (2003): 1st NLO, DIS.
- → HKM, HKN (2001-07): NLO, χ^2 minimization, DIS+DY.
- → EKPS07: LO, error analysis, 1st look at RHIC data.
- → EPS08: LO, BRAHMS forward data (factorization check).
- → EPS09: NLO, χ^2 minimization, error analysis.

Global fits:

→ Eskola '94: DGLAP for nuclei.

→ EI

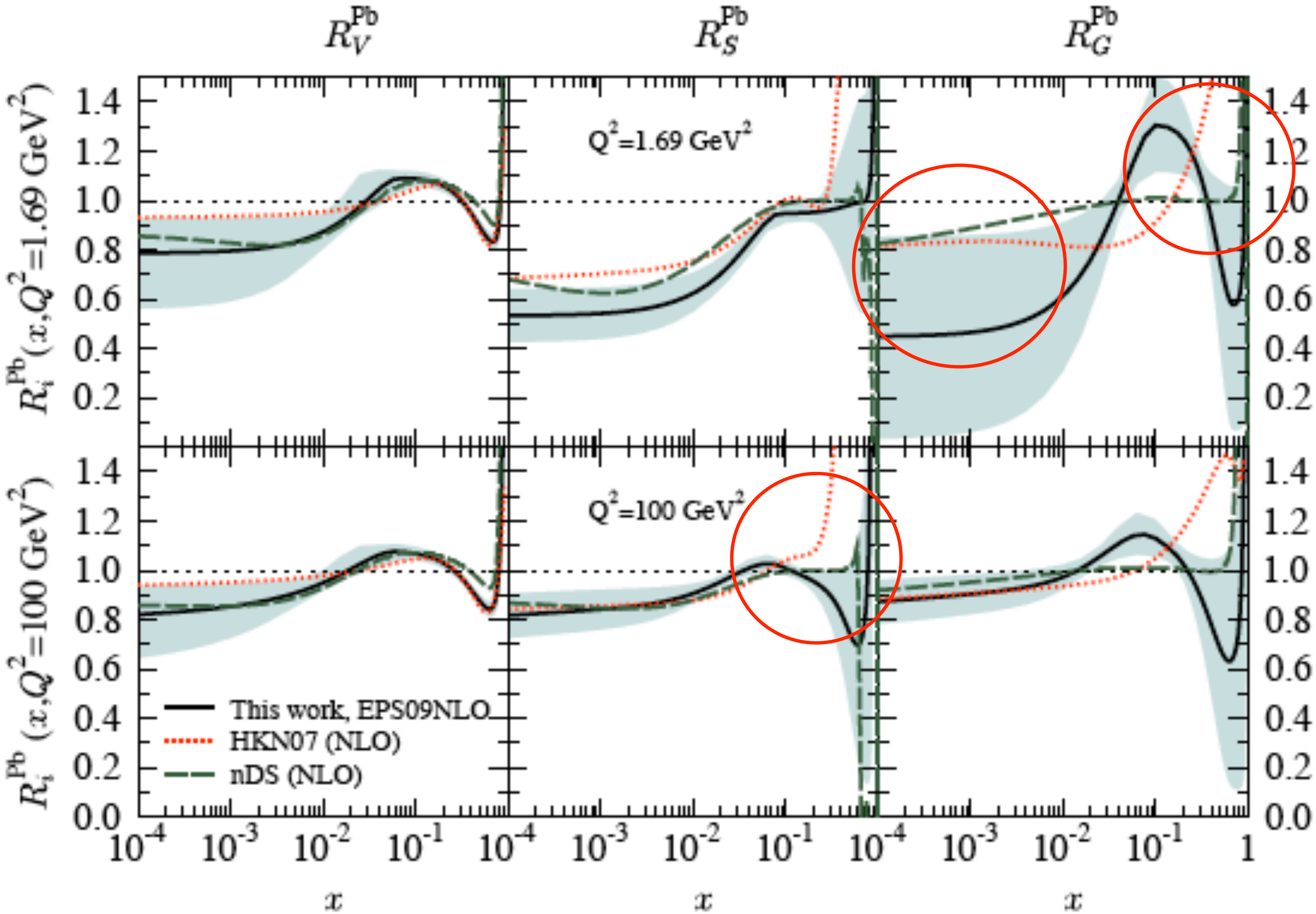
→ O

→ nI

→ H

→ EI

→ EI



→ EI 09: NLO, χ^2 minimization, error analysis.

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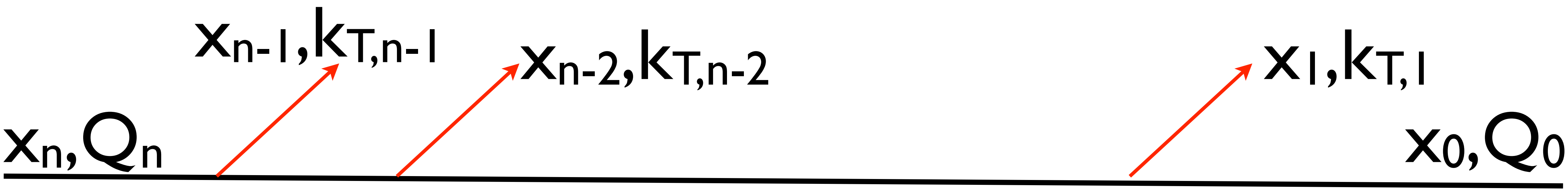
DGLAP/BFKL:



$$dP_i = \frac{dx_i}{x_i}\frac{dk_{T,i}^2}{k_{T,i}^2}, \quad \omega_i = x_i E, \quad \theta_i^2 \simeq \frac{k_{T,i}^2}{\omega_i^2} \quad x_n \ll x_{n-1} \ll x_{n-2} \ll \ldots \ll x_1 \ll x_0$$

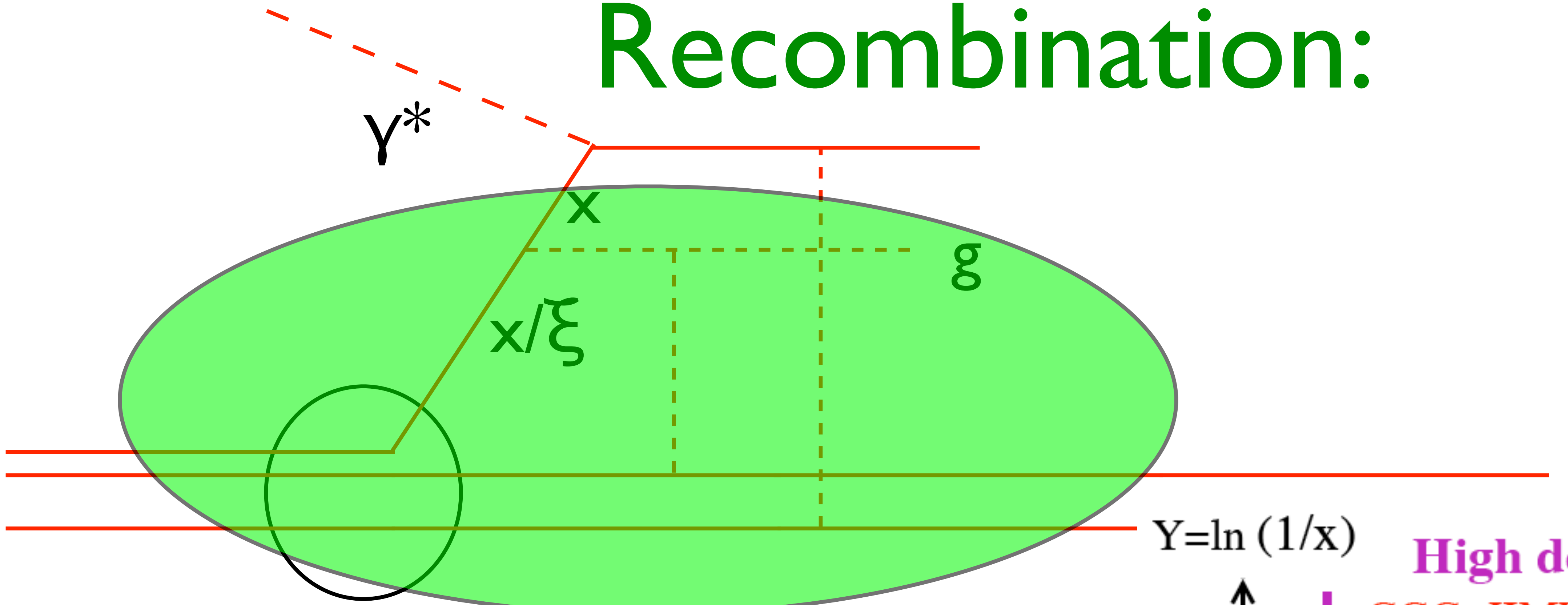
A) DGLAP (DLA): $$Q_n^2 \gg k_{T,n-1}^2 \gg k_{T,n-2}^2 \gg \ldots \gg k_{T,1}^2 \gg Q_0^2$$

$$\int_{Q_0}^{Q_n} dP_{n-1} \int_{Q_0}^{k_{T,n-1}} dP_{n-2} \ldots \int_{Q_0}^{k_{T,2}} dP_1 \propto \left[\frac{\alpha_s N_c}{\pi} \ln \frac{Q_n}{Q_0}\right]^n$$

B) BFKL: $$\int_{x_n}^{x_0} dP_{n-1} \int_{x_{n-1}}^{x_0} dP_{n-2} \ldots \int_{x_2}^{x_0} dP_1 \propto \left[\frac{\alpha_s N_c}{\pi} \ln \frac{x_0}{x_n}\right]^n$$

- Both of them lead to a gluon distribution at small x behaving like $xg(x,Q^2) \propto x^{-\lambda}$ at fixed Q^2, $\lambda \approx 0.2$-0.3 in data.

Recombination:

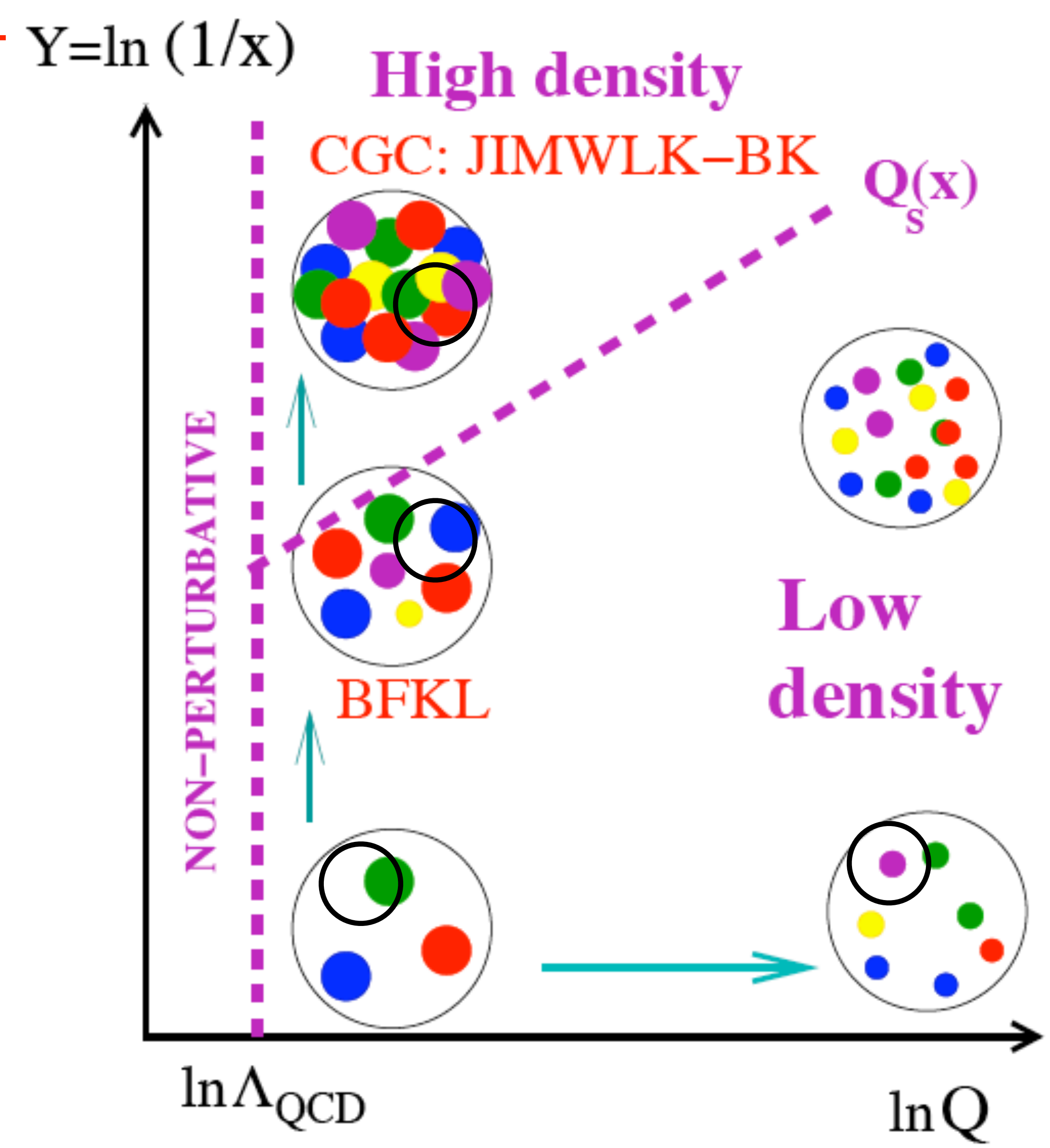


- At small x (gluon dominated), with the gluon increasing exponentially, we go from a linear regime:

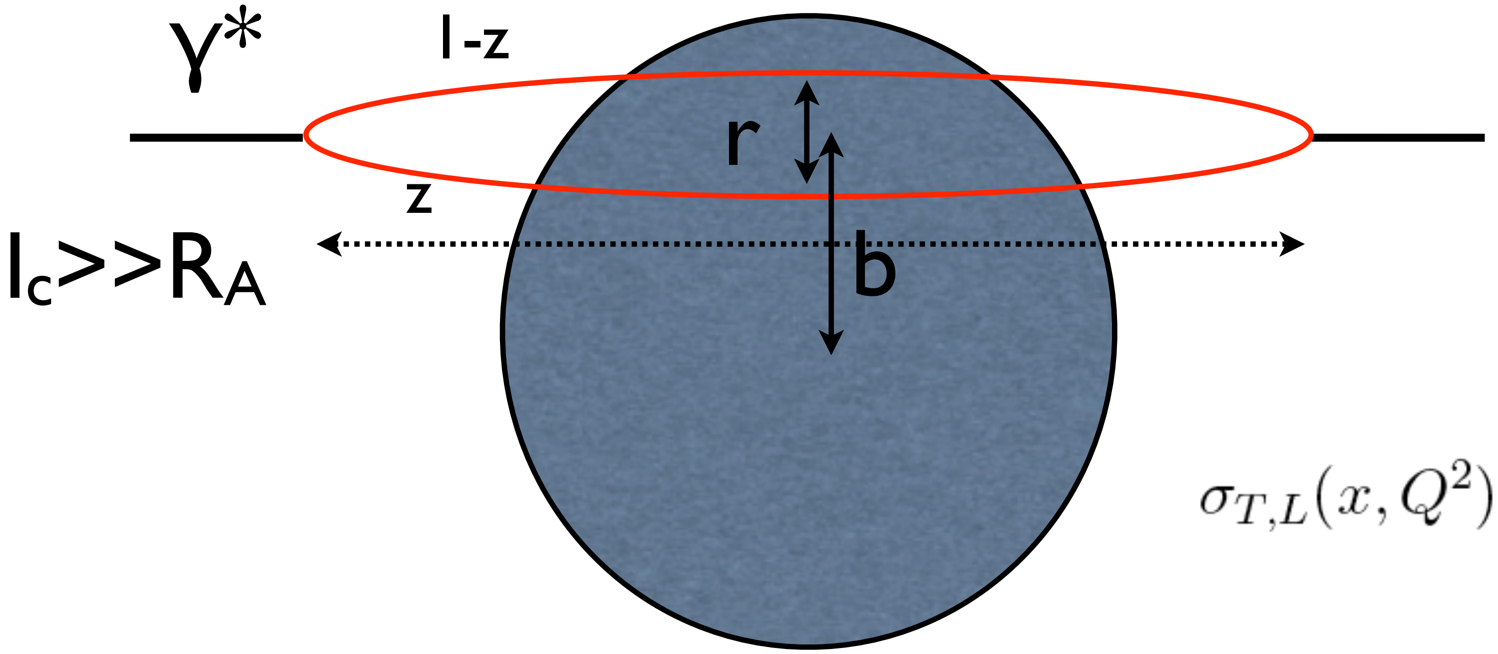
$\Delta xg \propto K \otimes xg$,

to a non-linear, recombination one whose first correction reads:

$\Delta xg \propto K \otimes xg - c(xg)^2$.



Unitarity:



$$F_2(x,Q^2) = \frac{Q^2}{4\,\pi^2\,\alpha_{em}}\,(\sigma_T + \sigma_L)$$

$$\sigma_{T,L}(x,Q^2) = \int_0^1 dz \int d\mathbf{b}\, d\mathbf{r}\, |\Psi_{T,L}(z,Q^2,\mathbf{r})|^2\, \mathcal{N}(\mathbf{b},\mathbf{r},x)$$

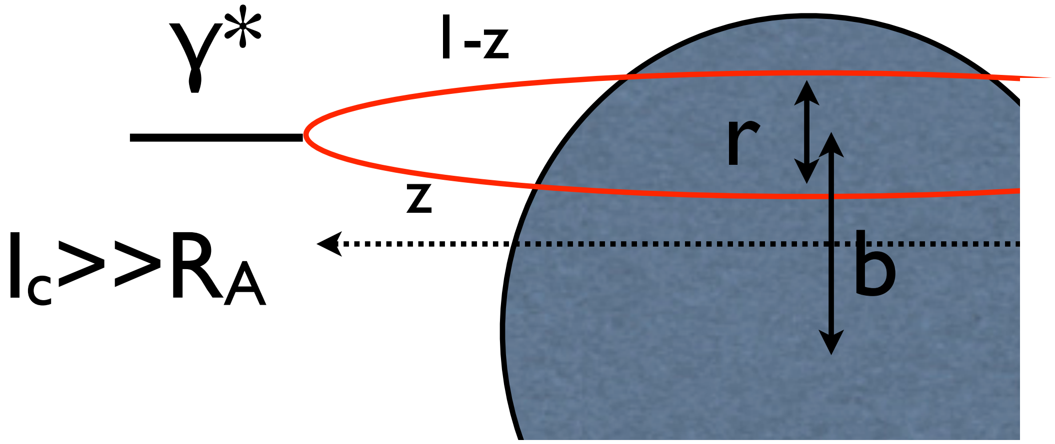
• Unitarity (probability conservation in QM) implies that the (Img forward) scattering amplitude $N \leq 1$ (optical theorem ⇒ $\sigma \propto N$). But

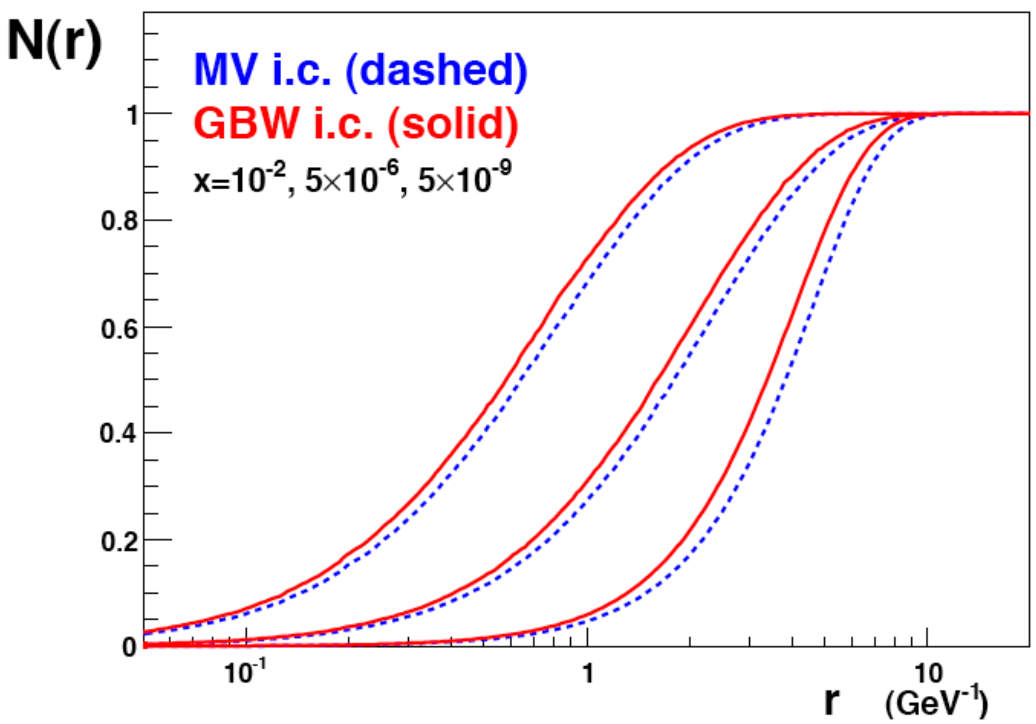
$$xg(x,Q^2) \propto \int^{Q^2} dk^2 \phi(x,k^2), \quad \phi(x,k^2) \propto \int \frac{d^2r}{r^2}\, e^{ik\cdot r} N(x,r)$$

so $xg(x,Q^2) \propto x^{-\lambda}$ at fixed Q^2 is not compatible with unitarity. The most celebrated dipole model is GBW, $Q_s^2 \propto x^{-\lambda}$.

$$\mathcal{N}^{GBW}(r, Y\!=\!0) = 1 - \exp\left[-\left(\frac{r^2\,Q_{s\,0}^2}{4}\right)^{\gamma}\right]$$

Unitarity:





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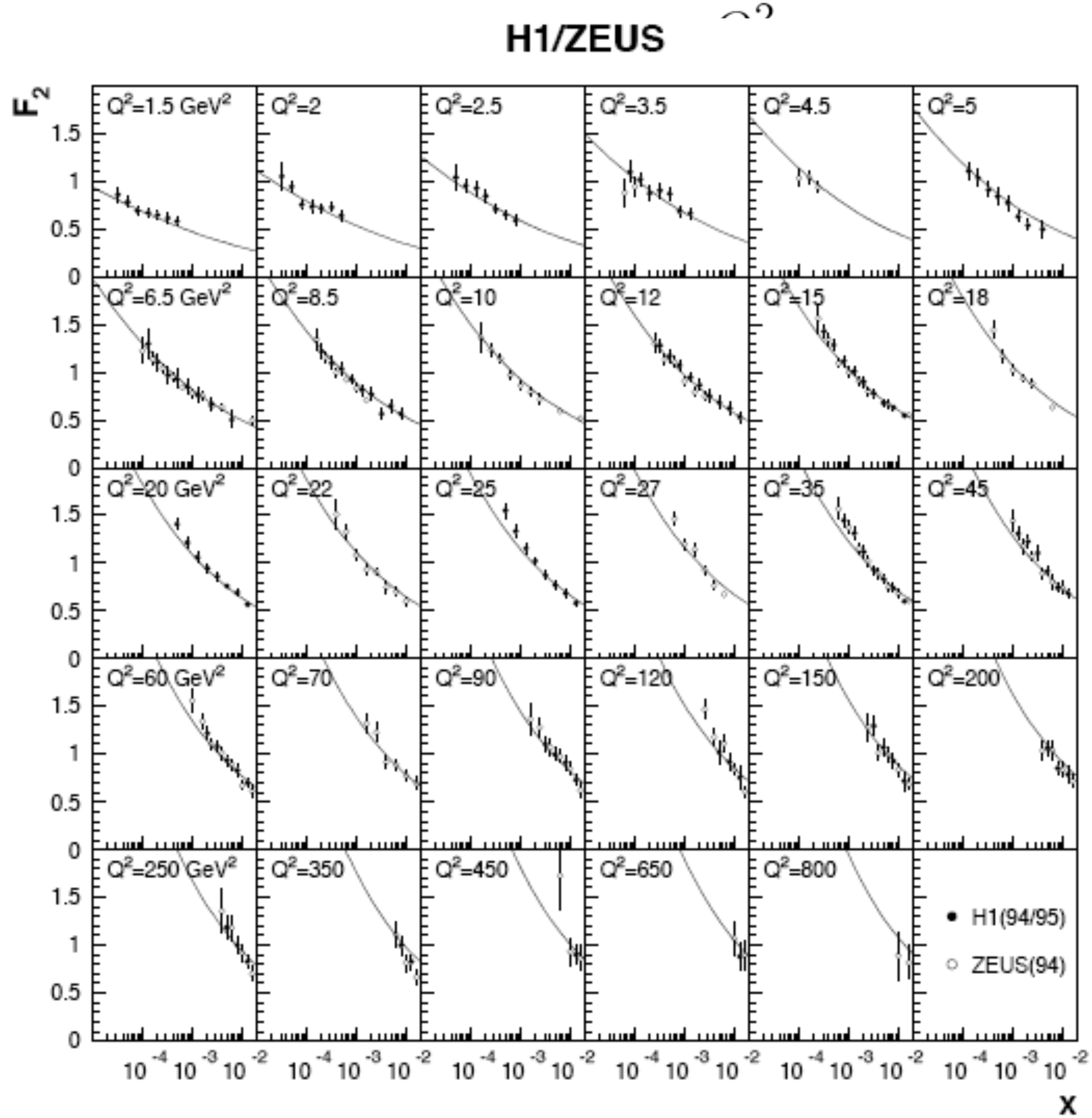
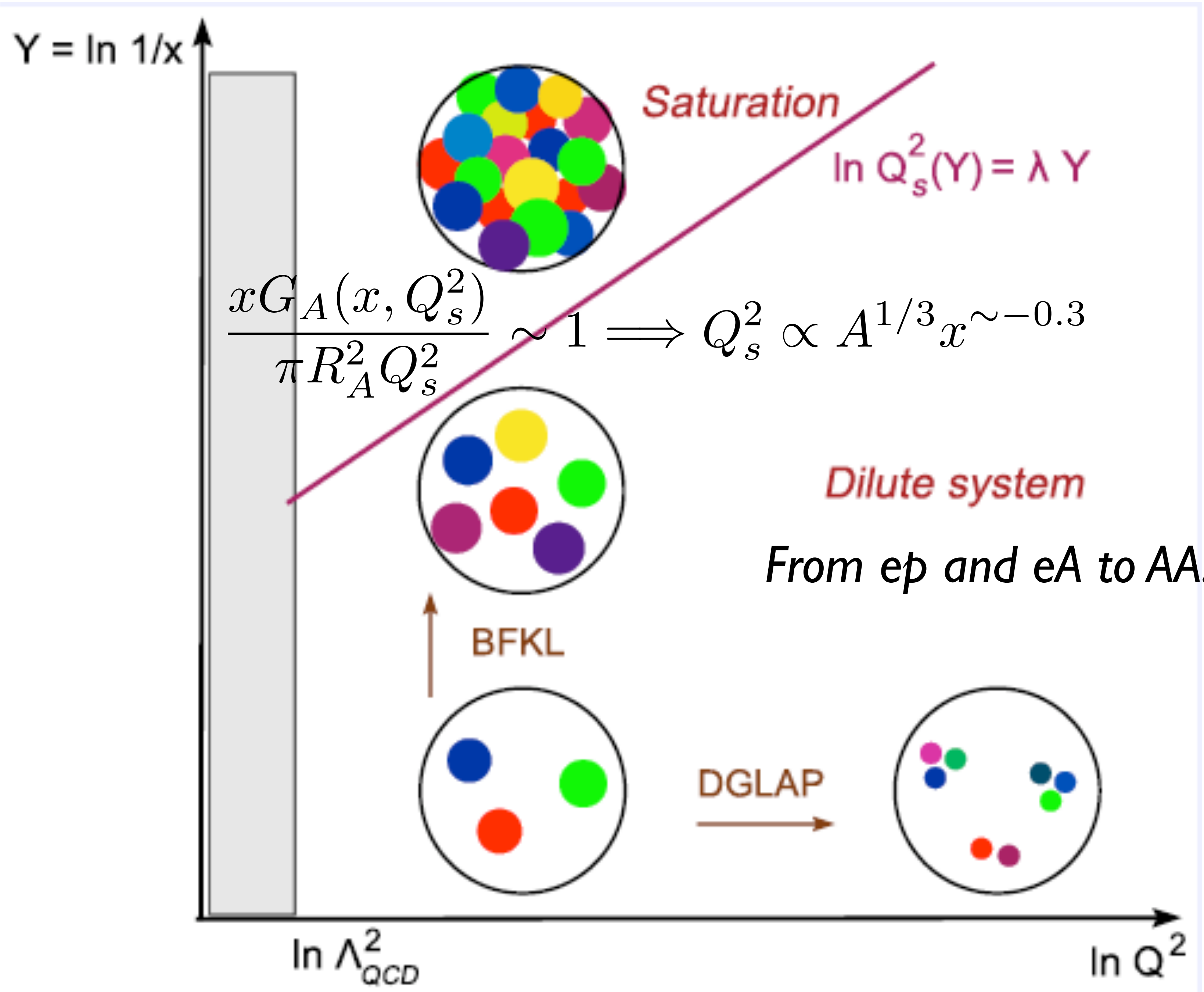


The ‘phase’ diagram:



From ep and eA to AA.

Origin in the early 80’s: GLR, Mueller et al, McLerran-Venugopalan.

Our aims: understanding

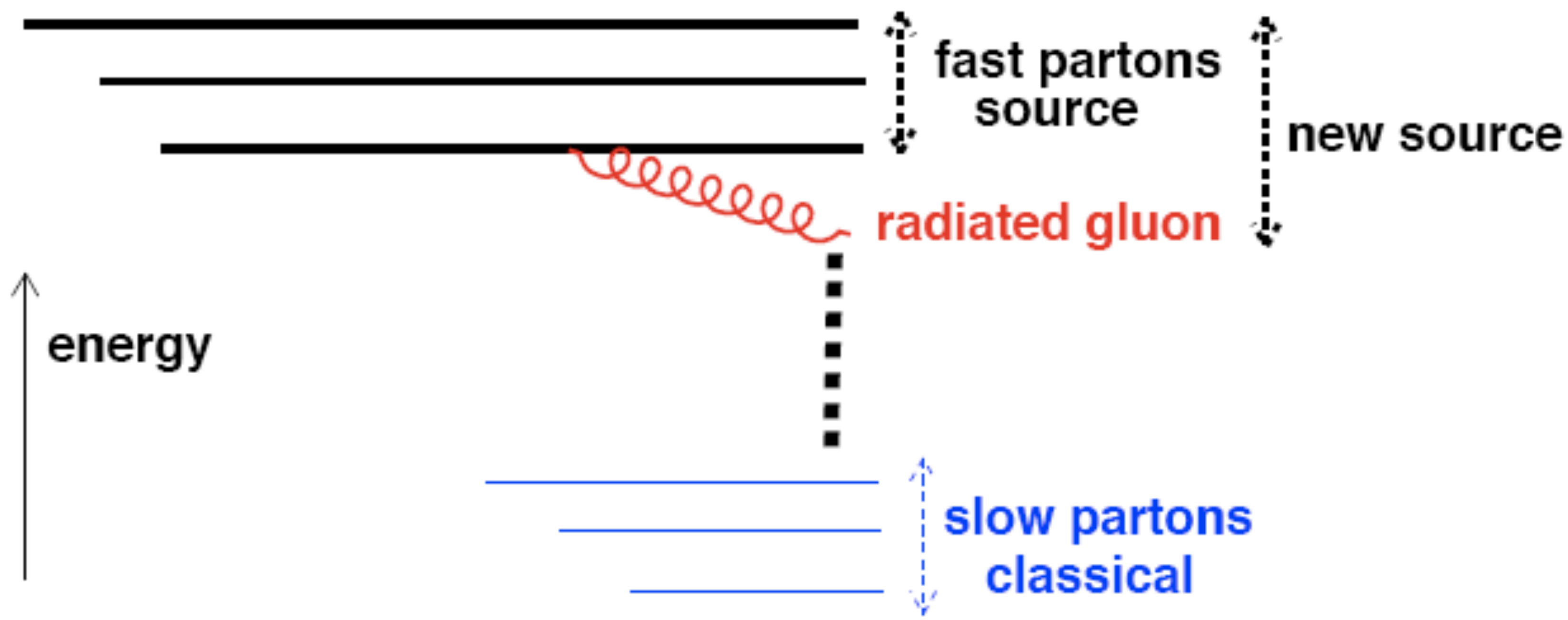
- The implications of unitarity in a QFT.
- The behavior of QCD at large energies.
- The hadron wave function at small x.
- The initial conditions for the creation of a dense medium in heavy-ion collisions.

Arguments:

- At **small enough x** for the projectile to interact coherently with the whole hadron, the CGC offers a description of the hadron wave function.

$$x \leq \frac{1}{2m_N R_A} \sim 0.1 A^{-1/3}$$

- The RG equation for the slow/fast separation (JIMWLK) was derived for scattering of a dilute projectile on a dense target. Gluon # becomes as high as it can (α_s^{-1}) be below Q_s^2.

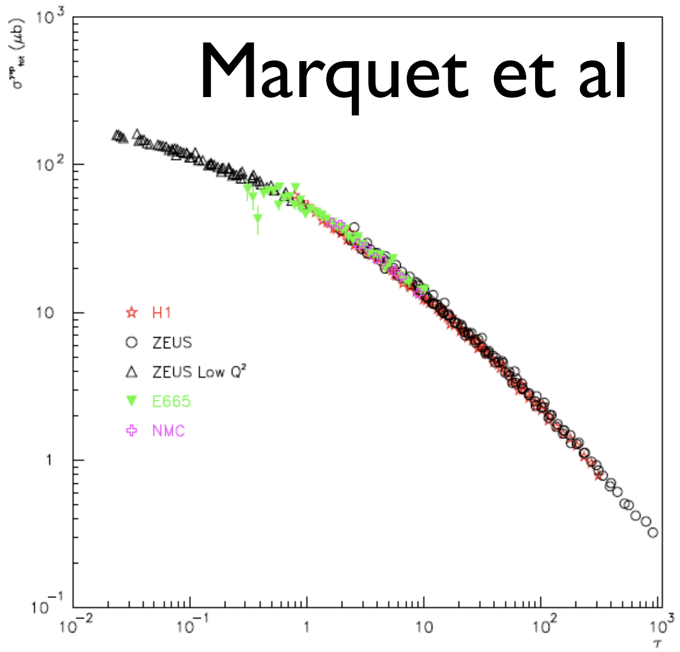


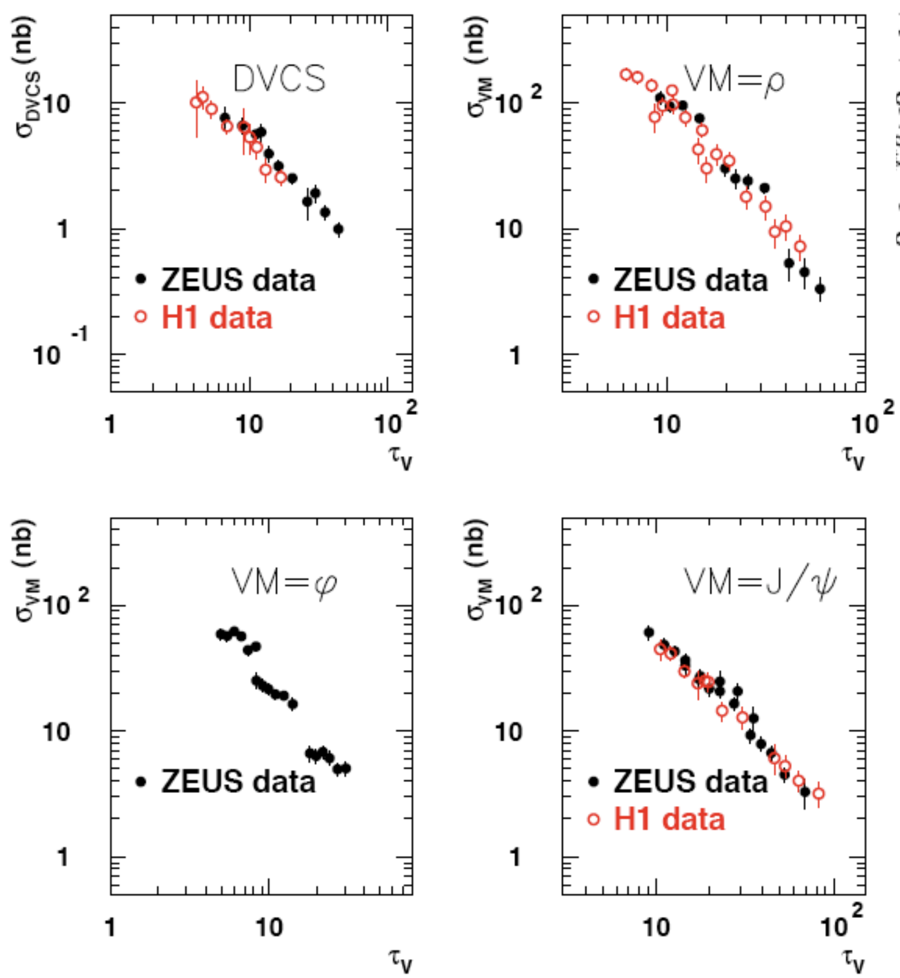
- Its mean-field version (the Balitsky-Kovchegov equation, **P2**) is used for phenomenology: numerically and analytically understood.

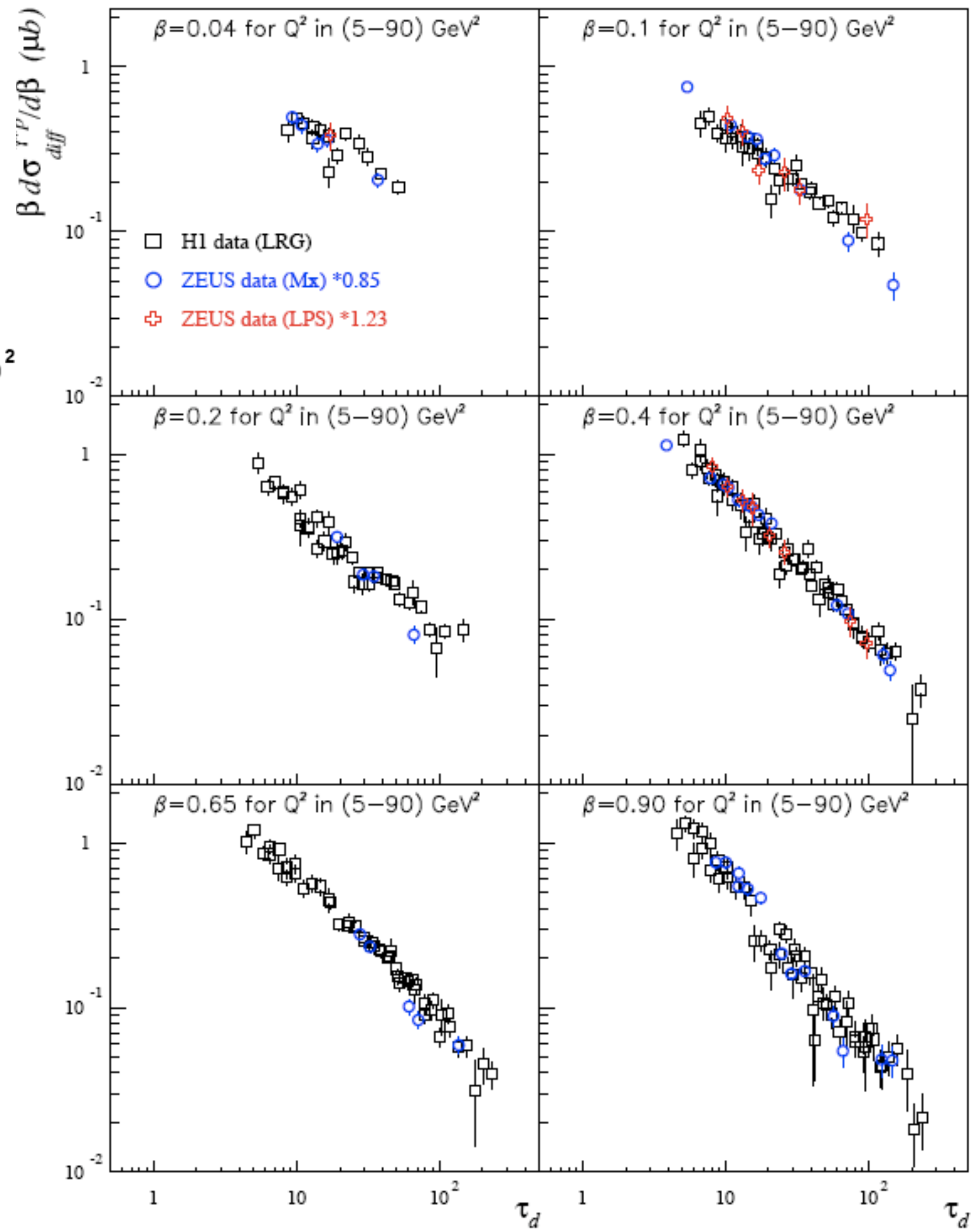
ep:

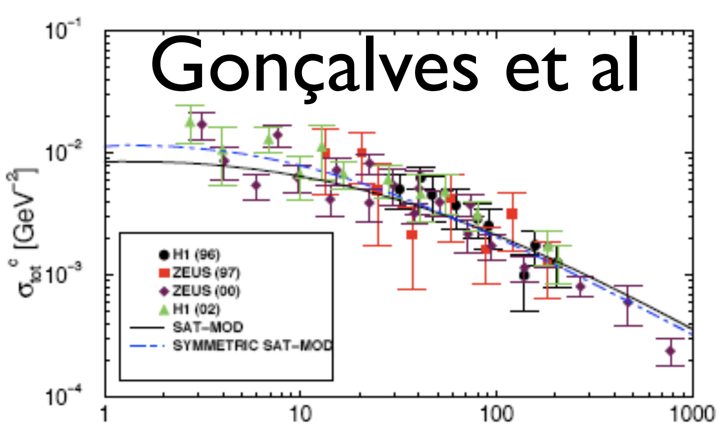
- The key feature of data is **geometric scaling** (Golec-Biernat et al).

$$\tau = \frac{Q^2}{Q_s^2(x)}, \quad \tau_D = \frac{Q^2}{Q_s^2(x_P)} \ \text{at fixed} \ \beta, \quad \tau_V = \frac{Q^2 + M_V^2}{Q_s^2(x_P)}$$









$$Q_s^2(x) = \left(\frac{x_0}{x}\right)^\lambda$$

$$\lambda_{(GBW)} \sim 0.25 \div 0.3$$

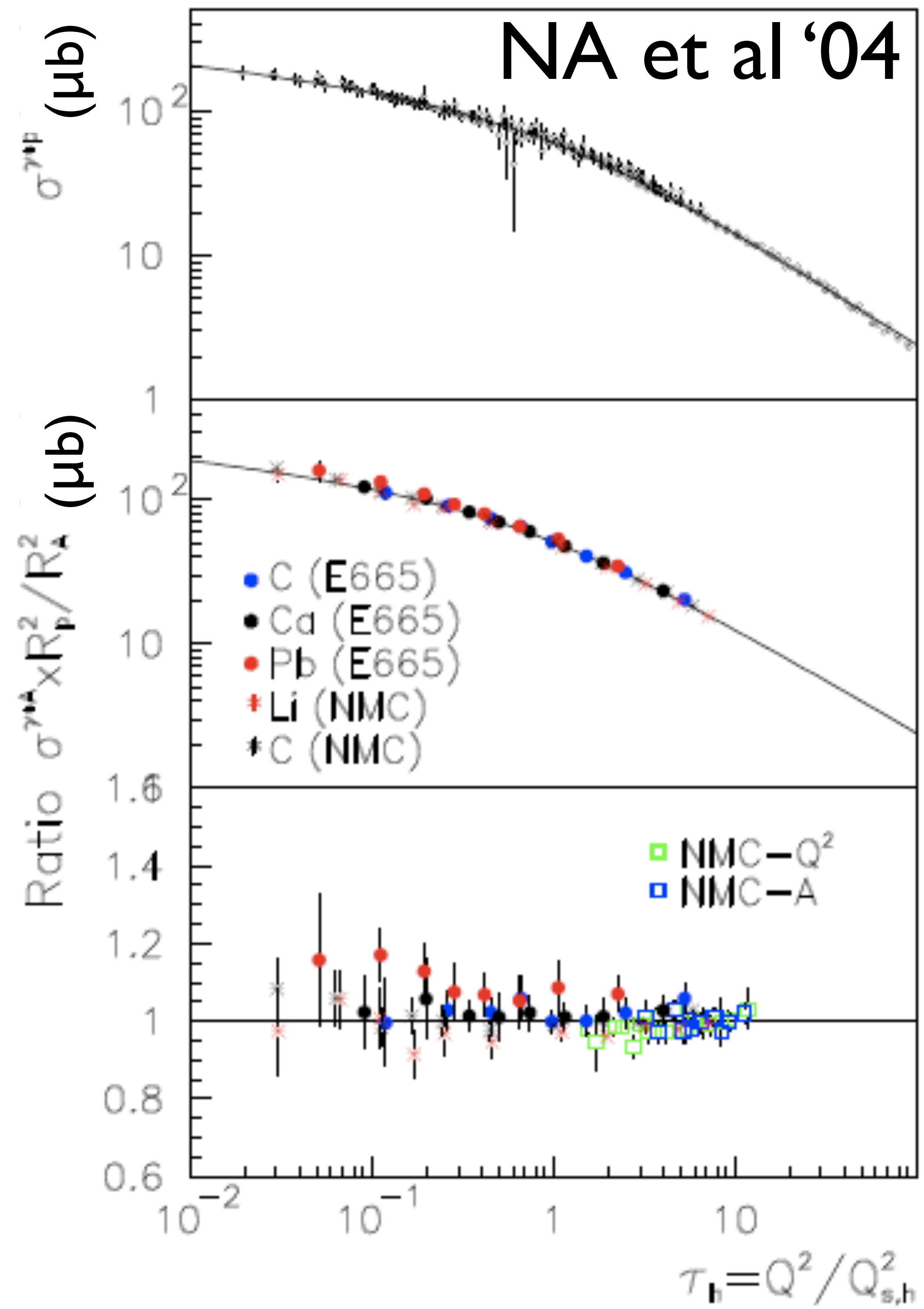
eA:

- Geometric scaling also found in eA.

$$\frac{\sigma^{\gamma^* A}(\tau_A)}{\pi R_A^2} = \frac{\sigma^{\gamma^* p}(\tau_A)}{\pi R_p^2}$$

$$\frac{Q_{\rm s,A}^2}{Q_{\rm s,p}^2} = \left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\frac{1}{\delta}} \Rightarrow \frac{\tau_A}{\tau_p} = \left(\frac{\pi R_A^2}{A\pi R_p^2}\right)^{\frac{1}{\delta}}$$

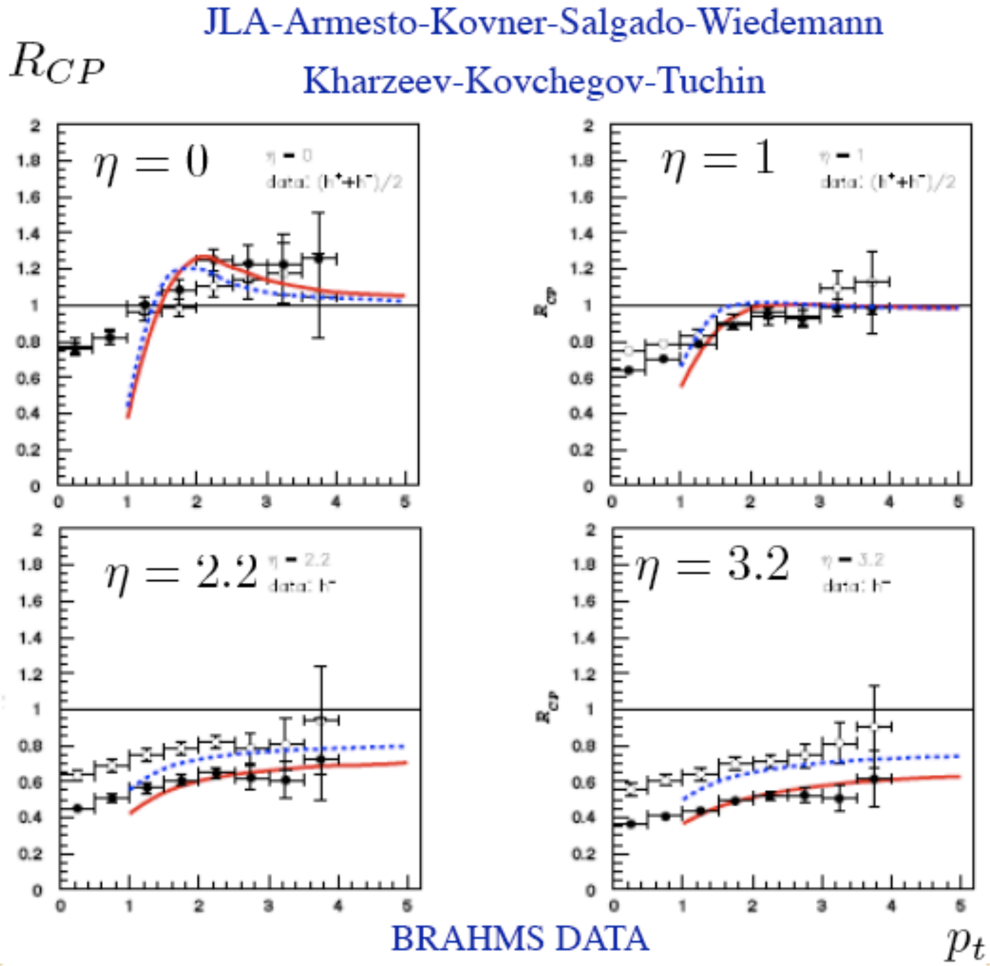
$\delta = 0.79 \pm 0.02$ $(x < 0.02)$.

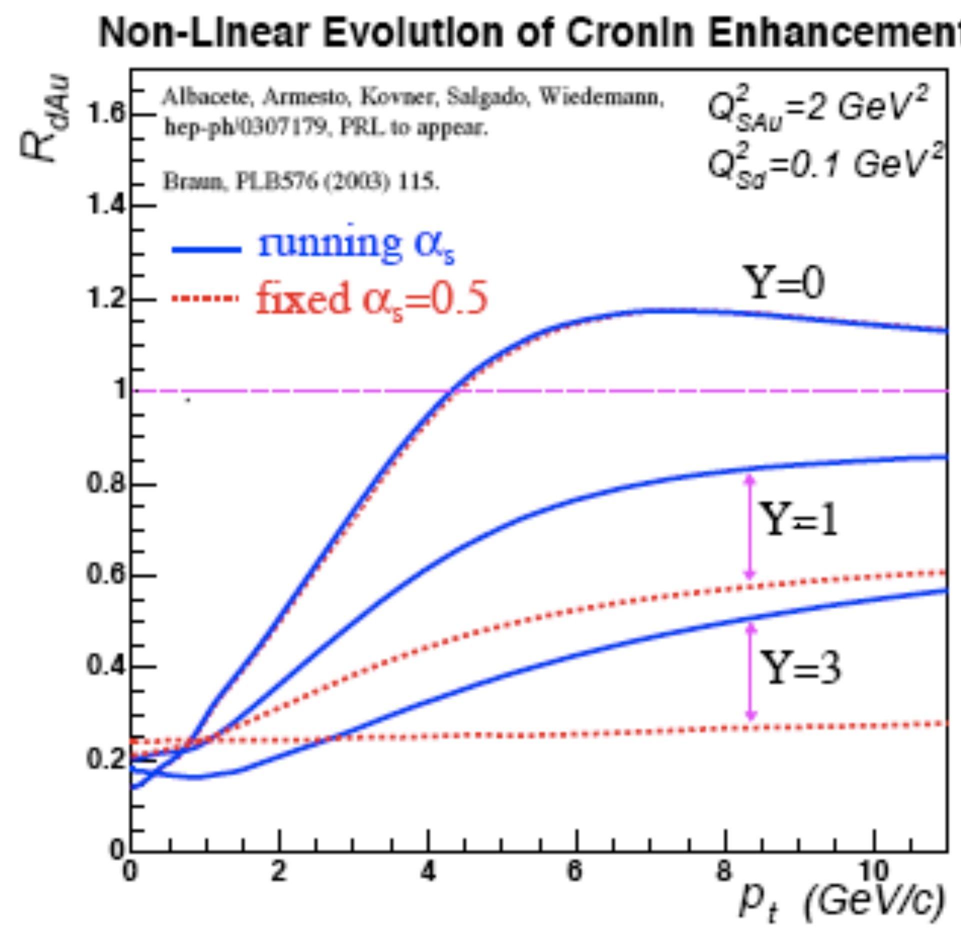


pA at RHIC:

- Control experiment for initial state effects in AA: Cronin effect in dAu at midrapidity ruled out initial state effects as the explanation for the suppression observed in AA.
- Suppression at forward rapidities was predicted by small-x evolution (BK).

$$R_{dAu} = \frac{\frac{dN^{dAu}}{d\eta d^2 b d^2 p}}{N_{coll} \frac{dN^{pp}}{d\eta d^2 b d^2 p}}$$

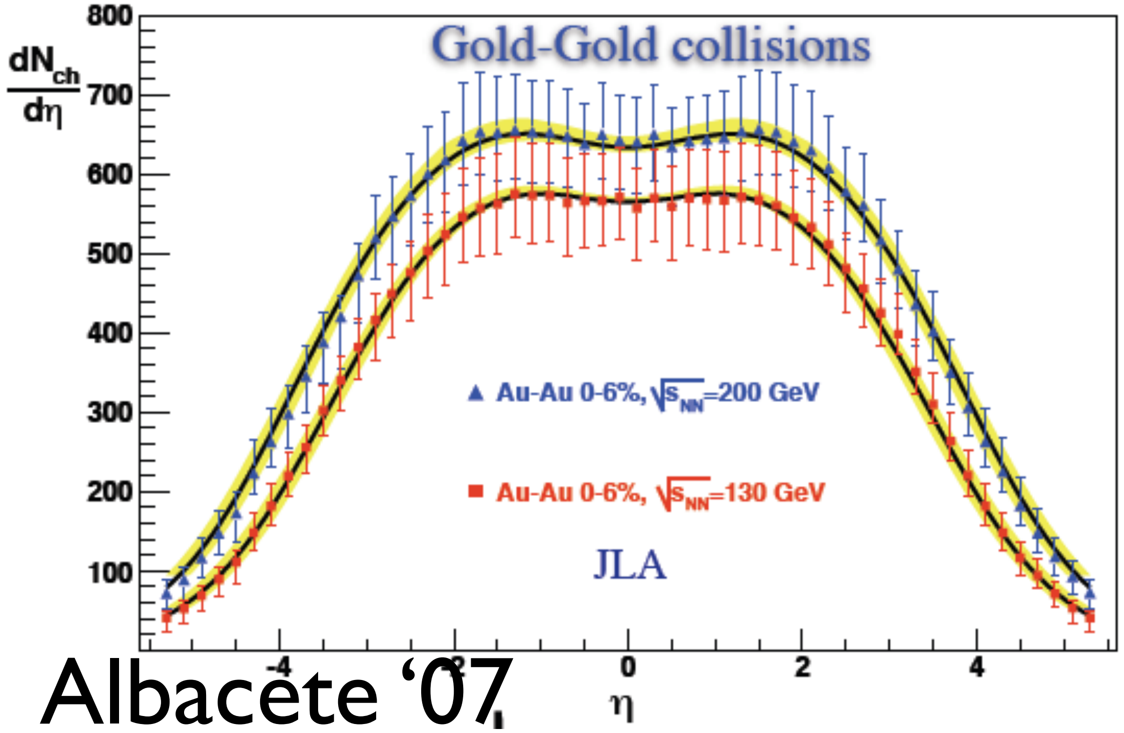




$$R_{dAu} \to_{y\to\infty} A^{-(1-\gamma/\delta)/3}(fc)$$

$$A^{-1/3}(rc, fluctuations)$$

AA at RHIC:

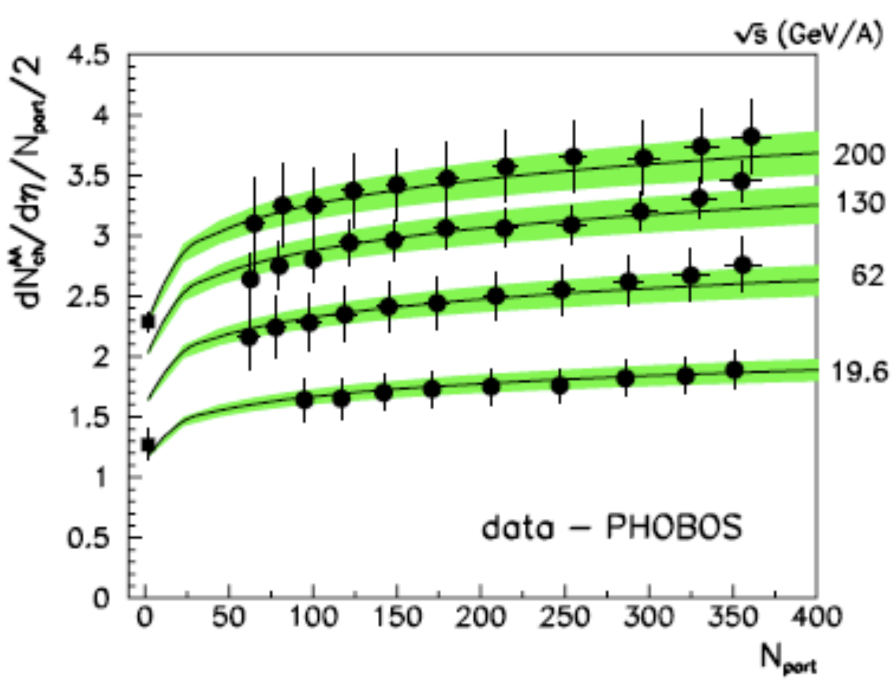


Albacete '07

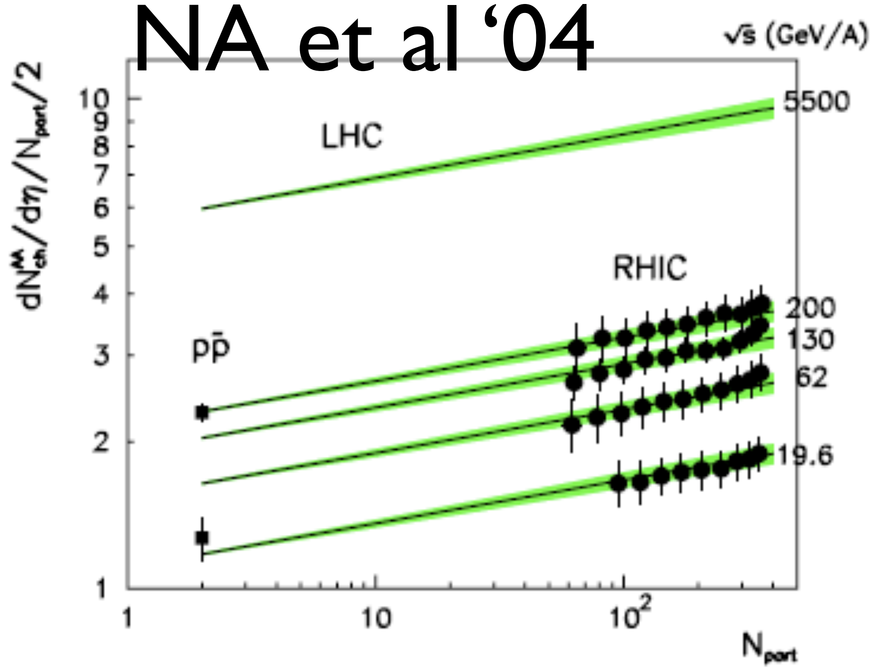
- Using factorization, multiplicities (evolution with centrality and pseudorapidity) can be computed.

$$\frac{1}{N_{part}} \frac{dN^g_{AA}}{d\eta}\bigg|_{\eta=0} \approx \begin{cases} \sqrt{s}^{\lambda} \ln\left(\sqrt{s}^{\lambda} N_{part}\right) & \text{Kharzeev-Levin Nardi} \\ \sqrt{s}^{\lambda} N_{part}^{\frac{1-\delta}{3\delta}} & \text{Armesto-Salgado Wiedemann} \end{cases}$$

- Now it has been done with the available NLO-BK machinery.



NA et al '04



- Geometric scaling is enough: factorization of geometry and energy dependences.

Contents:

1. Basic ideas about high-p_T particle and heavy flavor production.

2. Radiative energy loss.

3. DIS on nuclei.

4. Linear and non-linear evolution equations: saturation; the CGC.

5. Heavy-ion collisions at the LHC.

Present status:

Observable at RHIC	Standard interpretation
Low multiplicity (~2/3 expectations $dN_{ch}/d\eta\|_{\eta=0}$~1000 for central collisions)	Strong coherence in particle production: CGC, collectivity, strong gluon shadowing!?
v_2 in agreement with ideal hydro (η/s~a few/(4π))	Almost ideal fluid, very fast thermalization/ isotropization, strongly/weakly coupled!?
Strong jet quenching (R_{AA}(10 GeV) ~0.2 for π^0, disappearance of back-to-back correlations)	Opaque partonic medium, radiative (+elastic) energy loss, weak/strong interaction with the medium!?

All these observation have triggered new theoretical developments (e.g. how to treat a strongly coupled system - AdS/CFT) to:

- Check our theoretical explanations of the probes.
- Constrain our understanding of medium properties.

Open problems:

• Highlight: the medium created in the collisions is dense, ~10 GeV/fm^3, partonic and behaves very early like a quasi-ideal fluid; strong collectivity: scQGP. New theoretical developments:

A) Why the medium gets thermalized so early (τ<1 fm)? Instabilities, perturbative HO processes, strong coupling phenomena (studied in N=4 SYM using the AdS/CFT correspondence), CGC.

B) The value of qhat is? too large for pQCD: strong coupling?

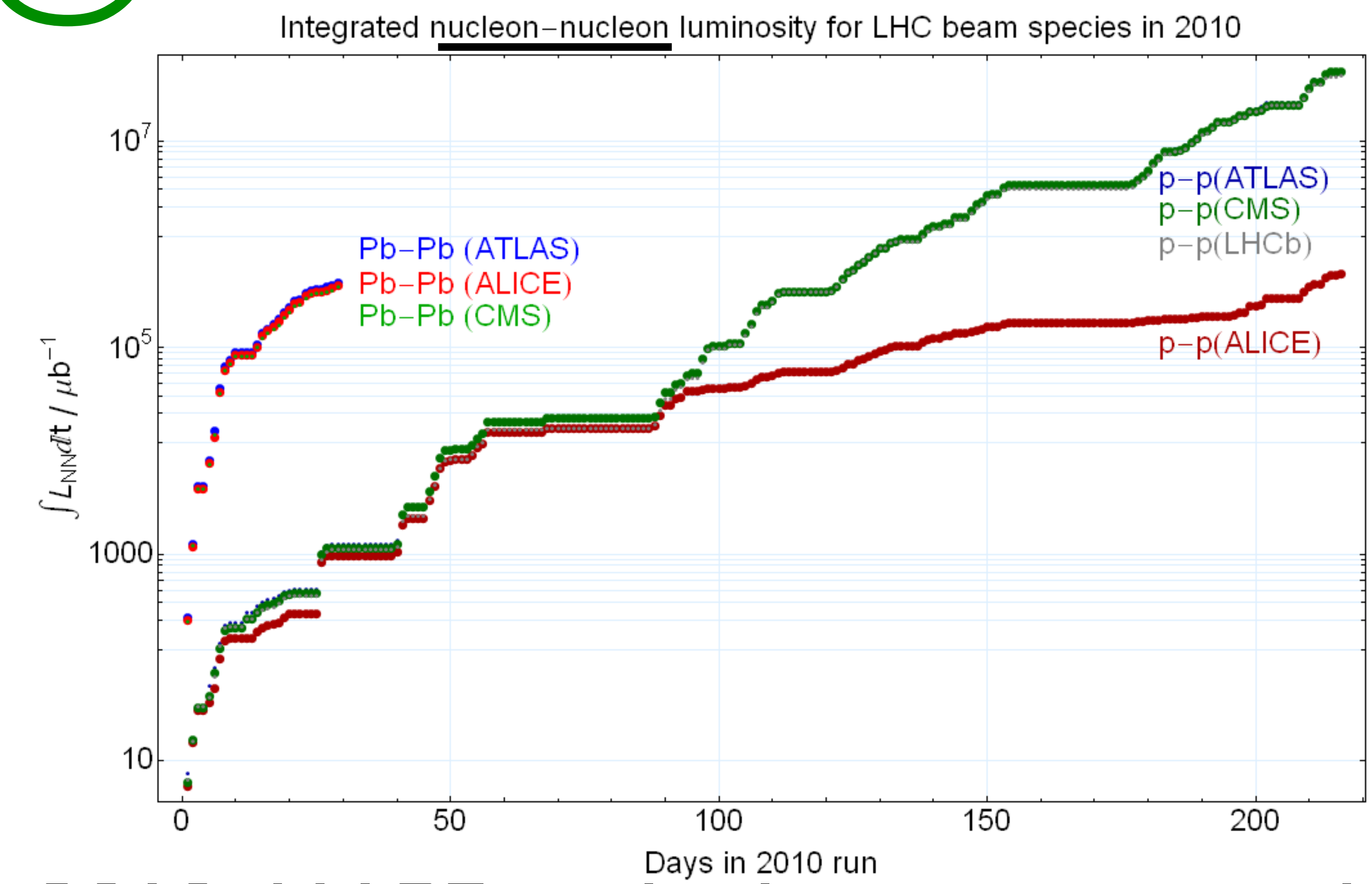
C) Why the viscosity is so low? How to do viscous hydro?

D) Differential observables; and jet-medium interactions?

HIC@LHC:

• LHC started accelerating ion beams on 04.11. 2010: 2.76 ATeV.

• 1st collisions on 07.11.2010; now ~ 10^8 recorded events in ALICE+ATLAS+CMS.



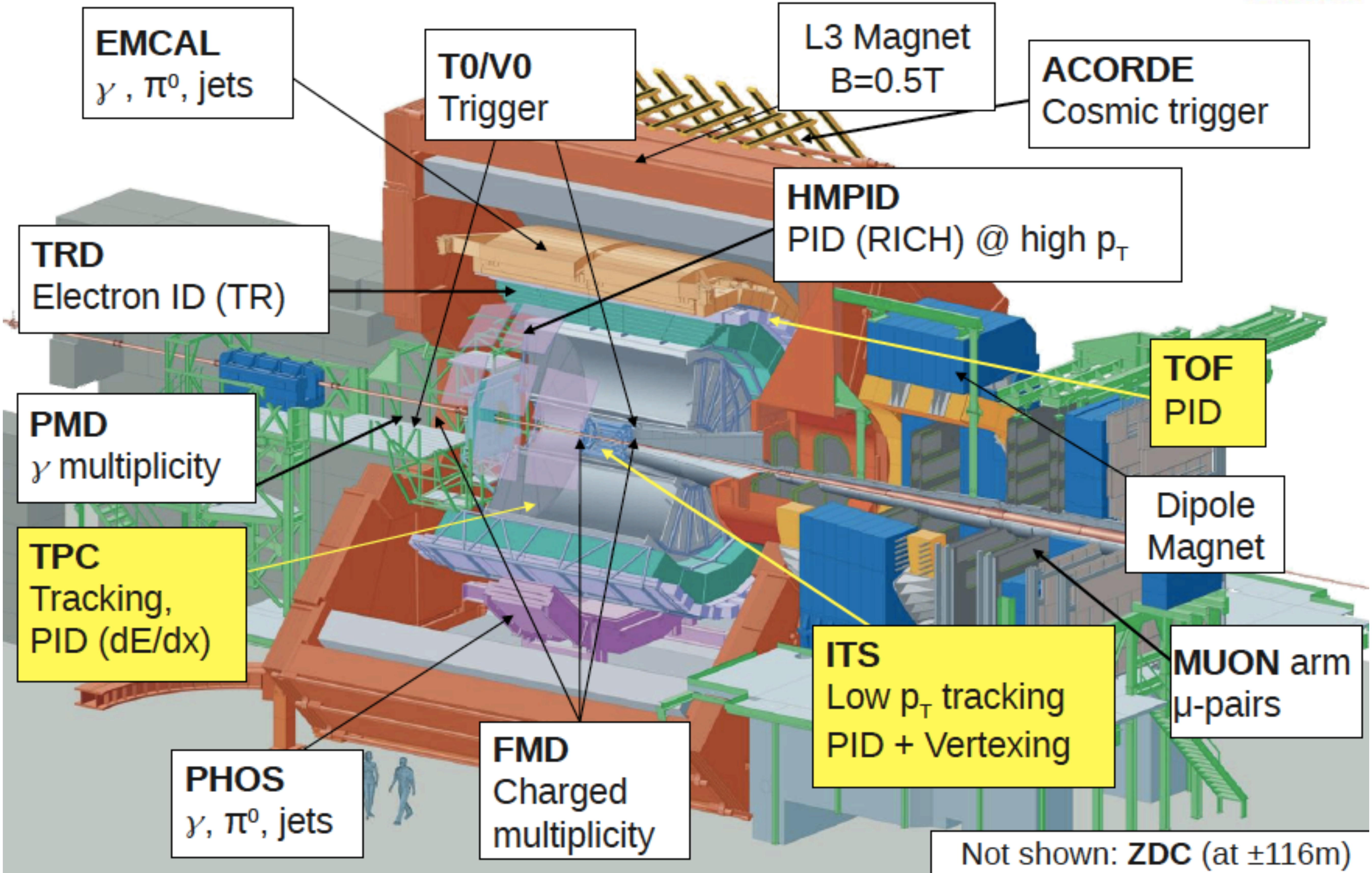
• First paper on arXiv on 17.11.2010: ALICE, multiplicities in central collisions, arXiv:1011.3916 [nucl-ex].

• 12 papers until now:

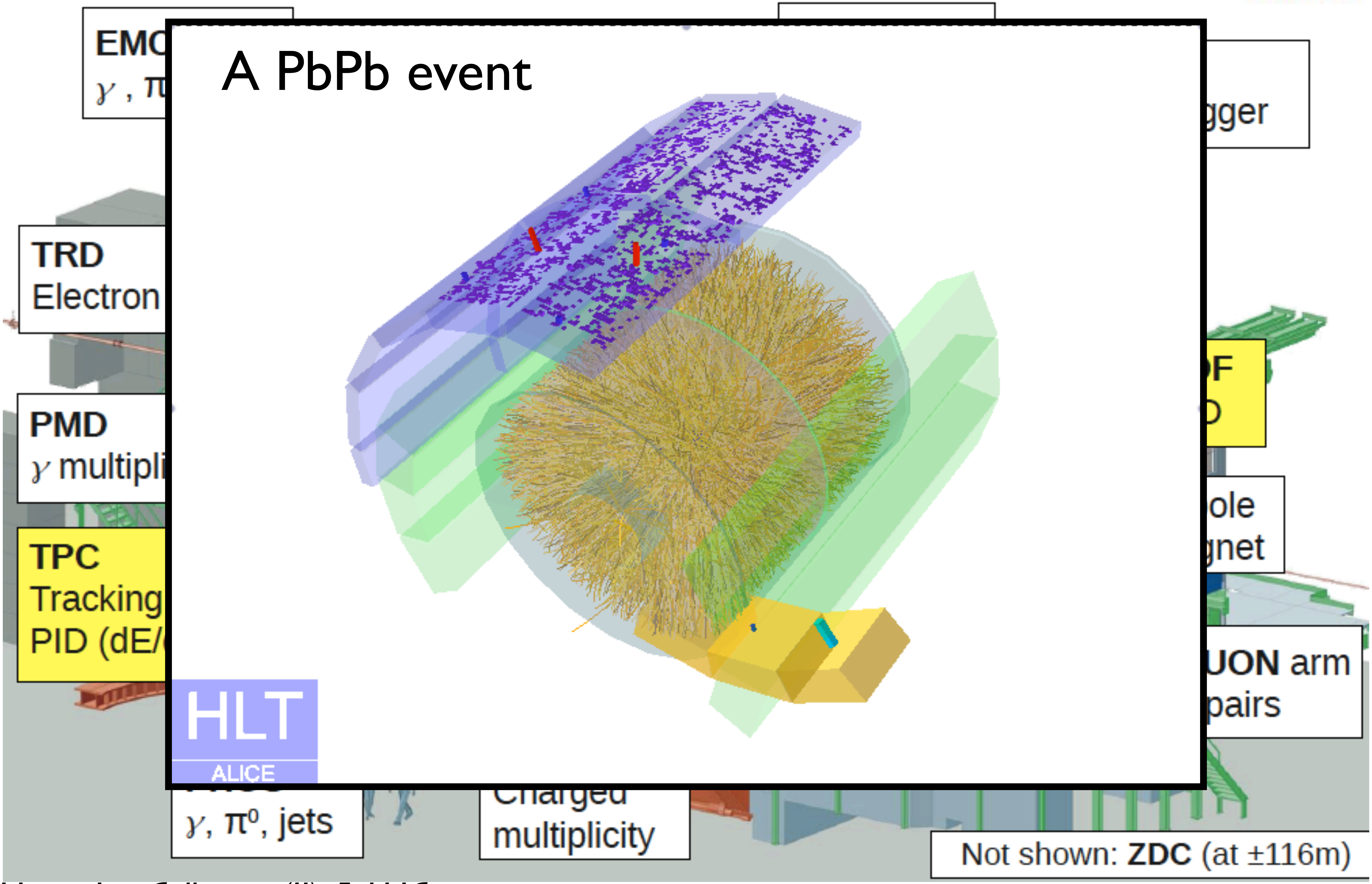
* ALICE: 6 (2 on multiplicities, 2 on flow, 1 on jet quenching, 1 on interferometry).
* ATLAS: 2 (1 on jets, 1 on J/ψ and Z).
* CMS: 4 (1 on jets, 1, on W/Z, 1 on correlations, 1 on quarkonia).

+ many new results in QM2011(http://qm2011.in2p3.fr/).

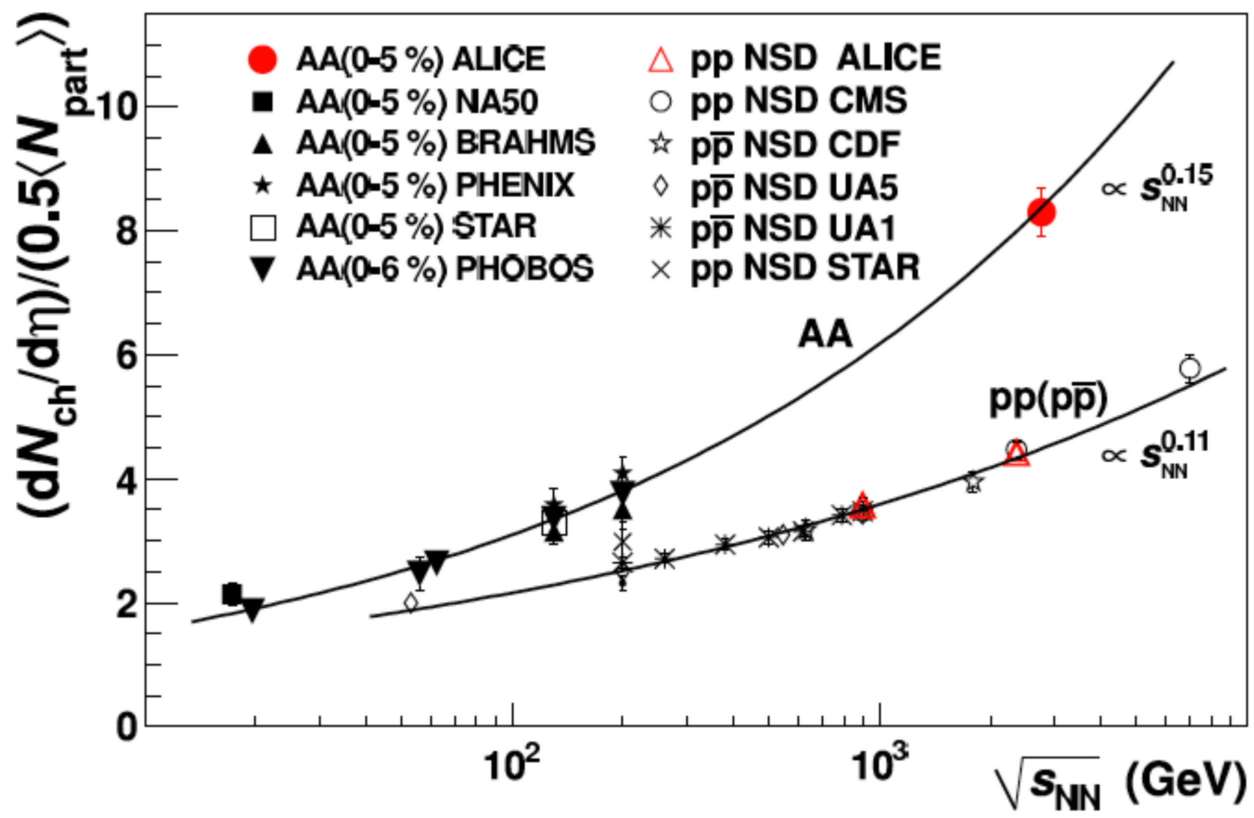
A Large Ion Collider Experiment

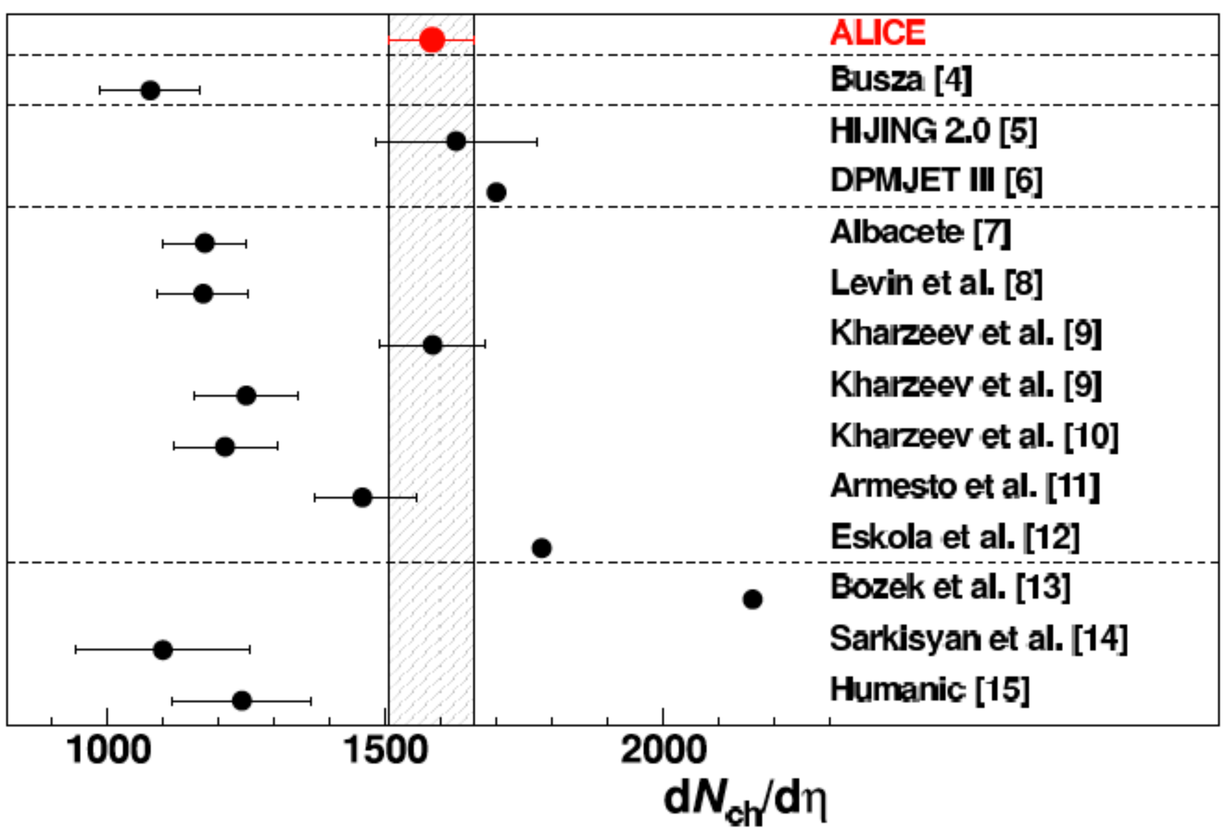


A Large Ion Collider Experiment



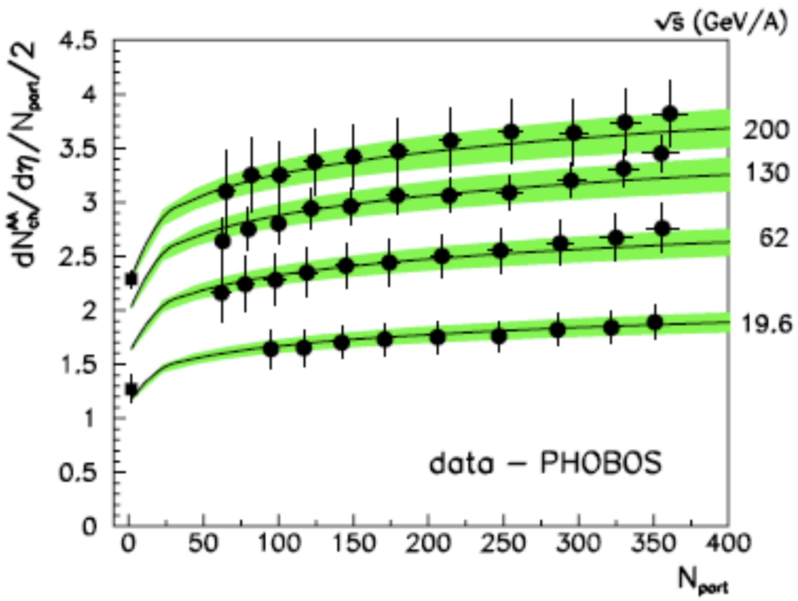
ALICE data on multiplicities:



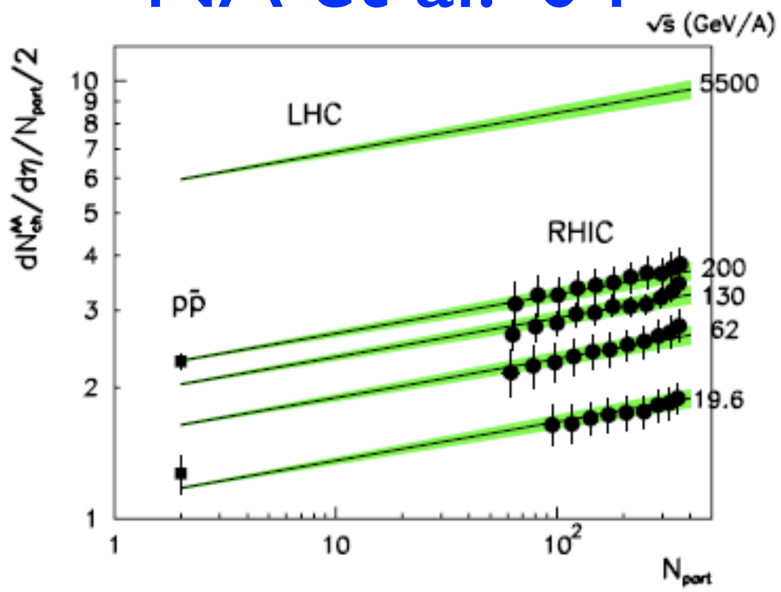


- Multiplicity larger than expected in data-driven extrapolations.
- In agreement with saturation models (based on the behavior of the small-x glue).
- Problems to reconcile the energy behavior of pp and AA.

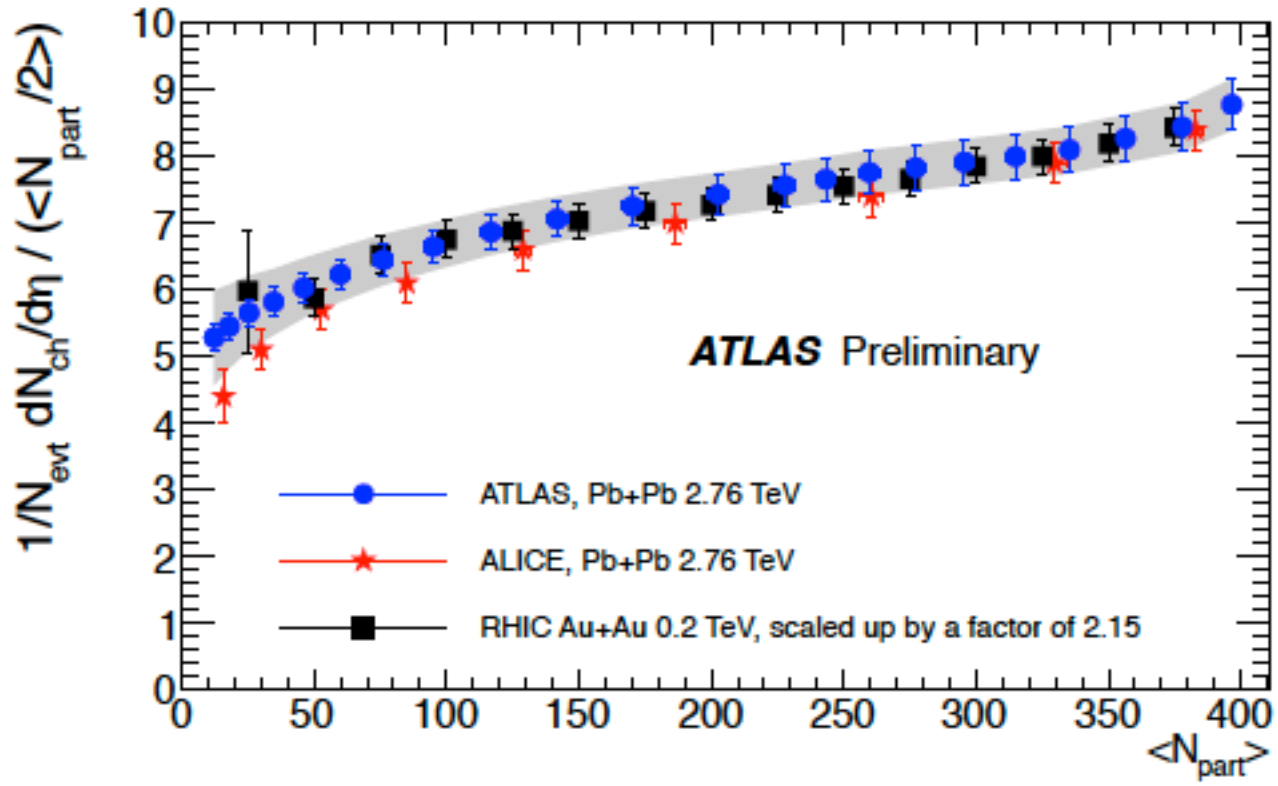
ALICE data on centrality:

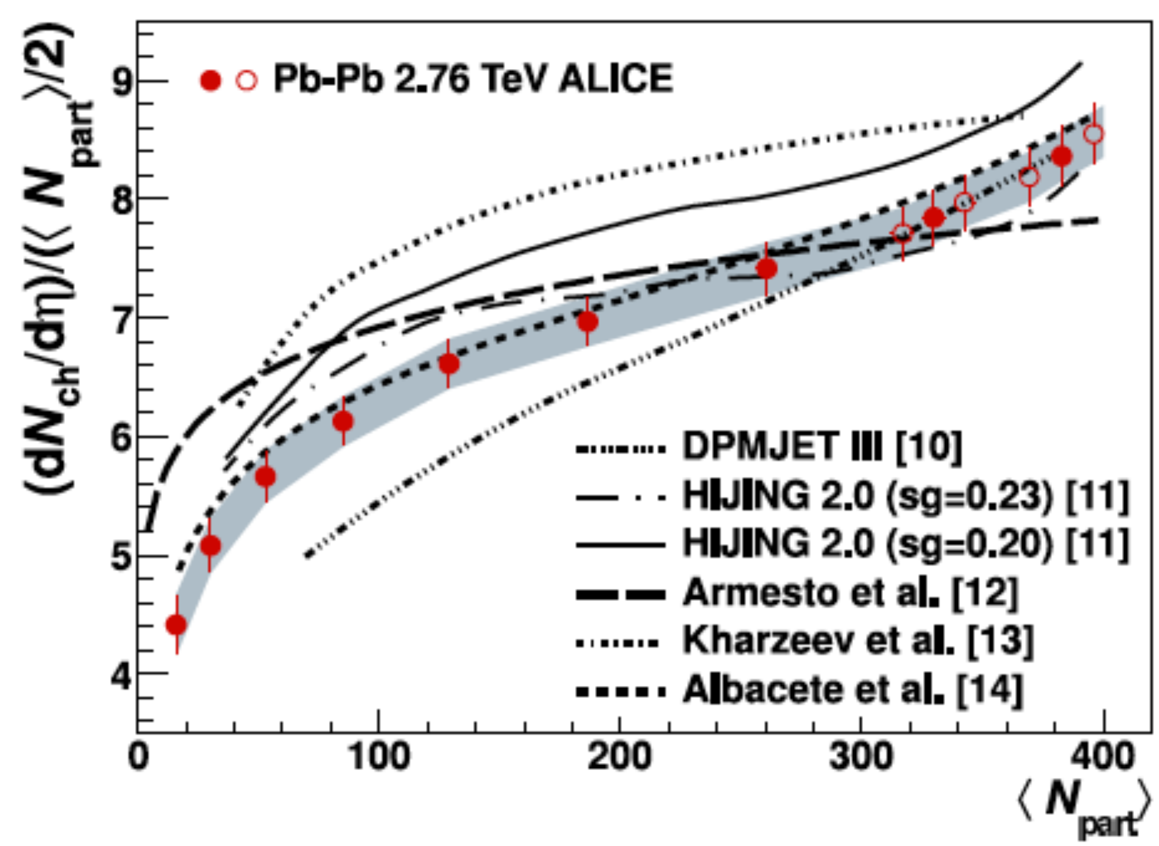


NA et al. '04

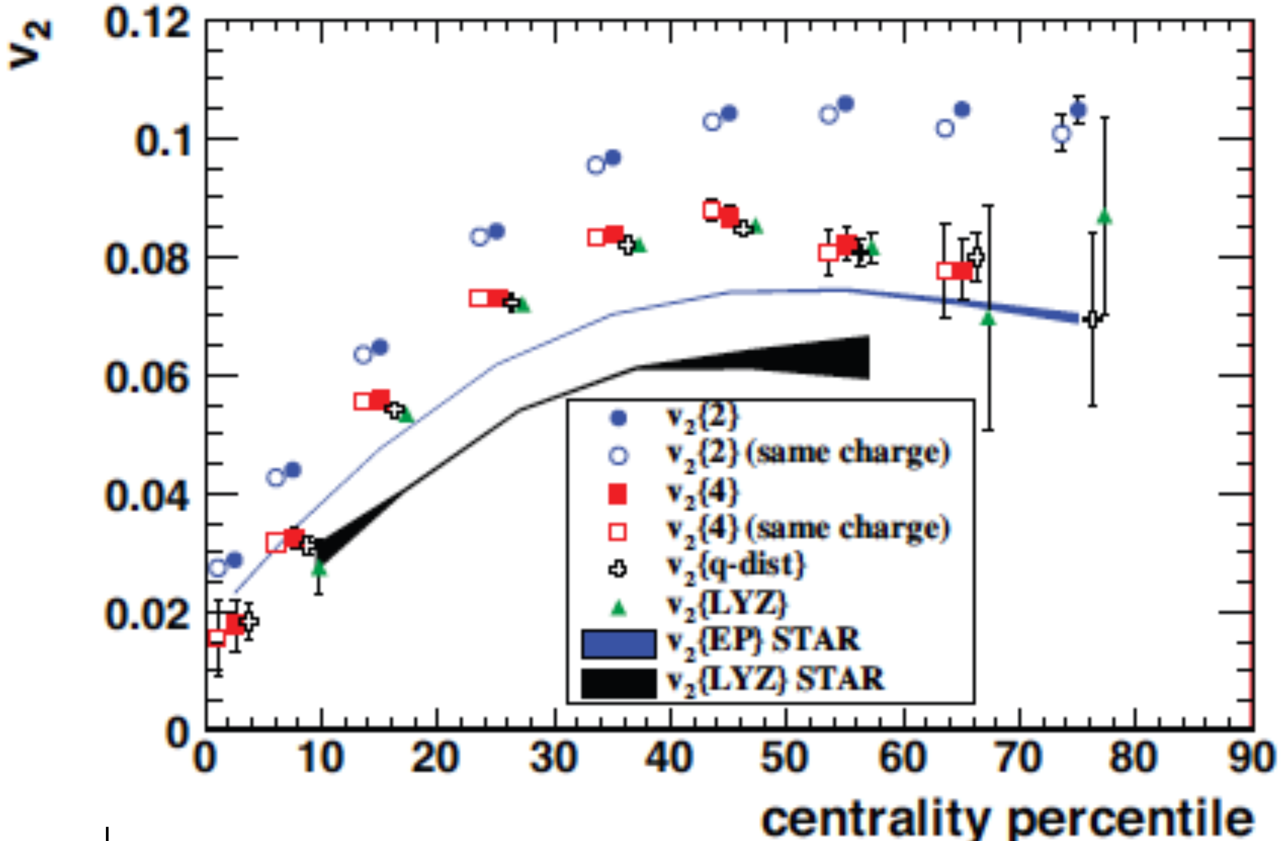


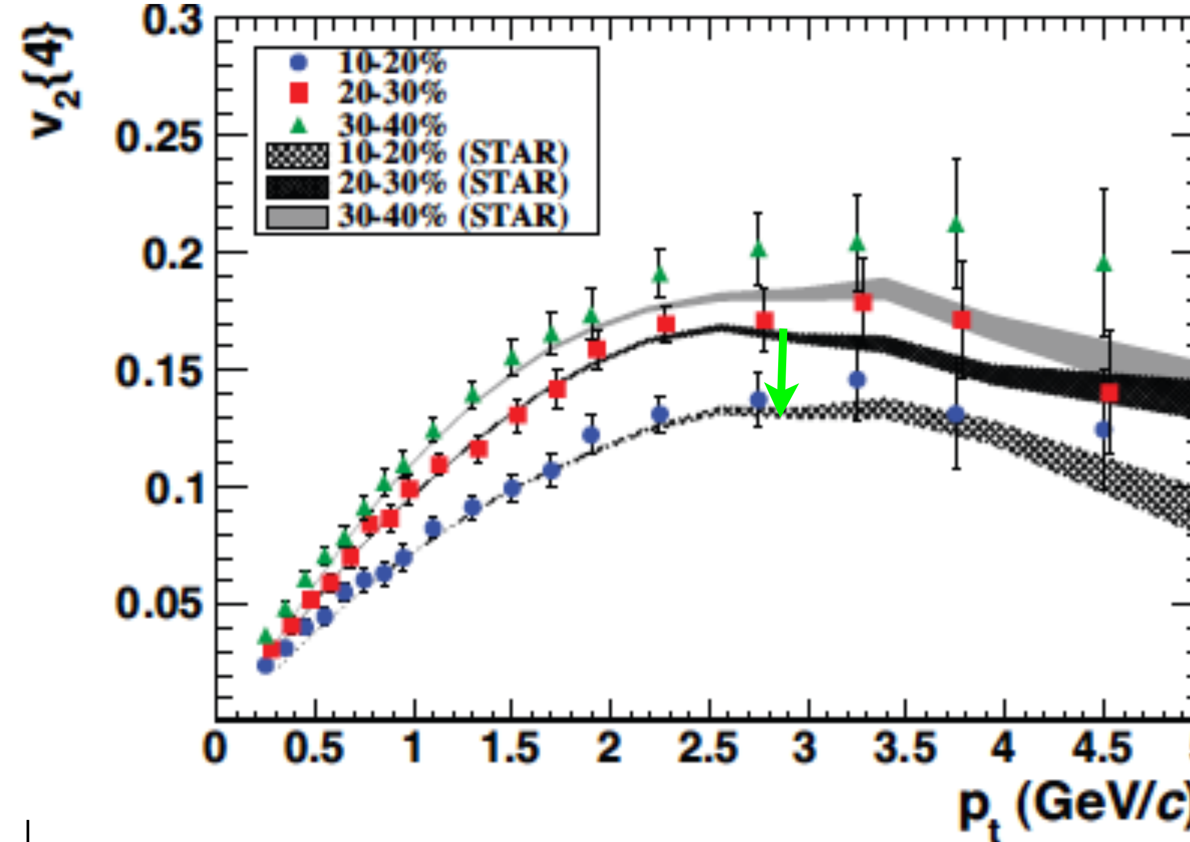
- Behavior compatible with factorization between energy and centrality dependences, as suggested by saturation.



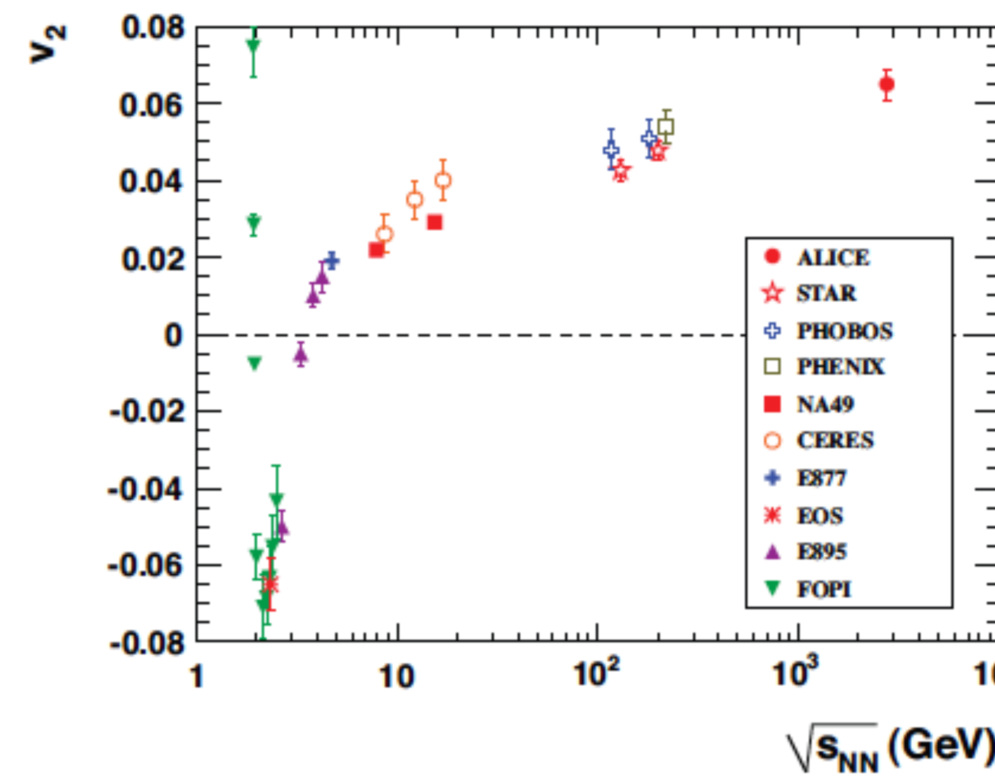


Azimuthal asymmetries:



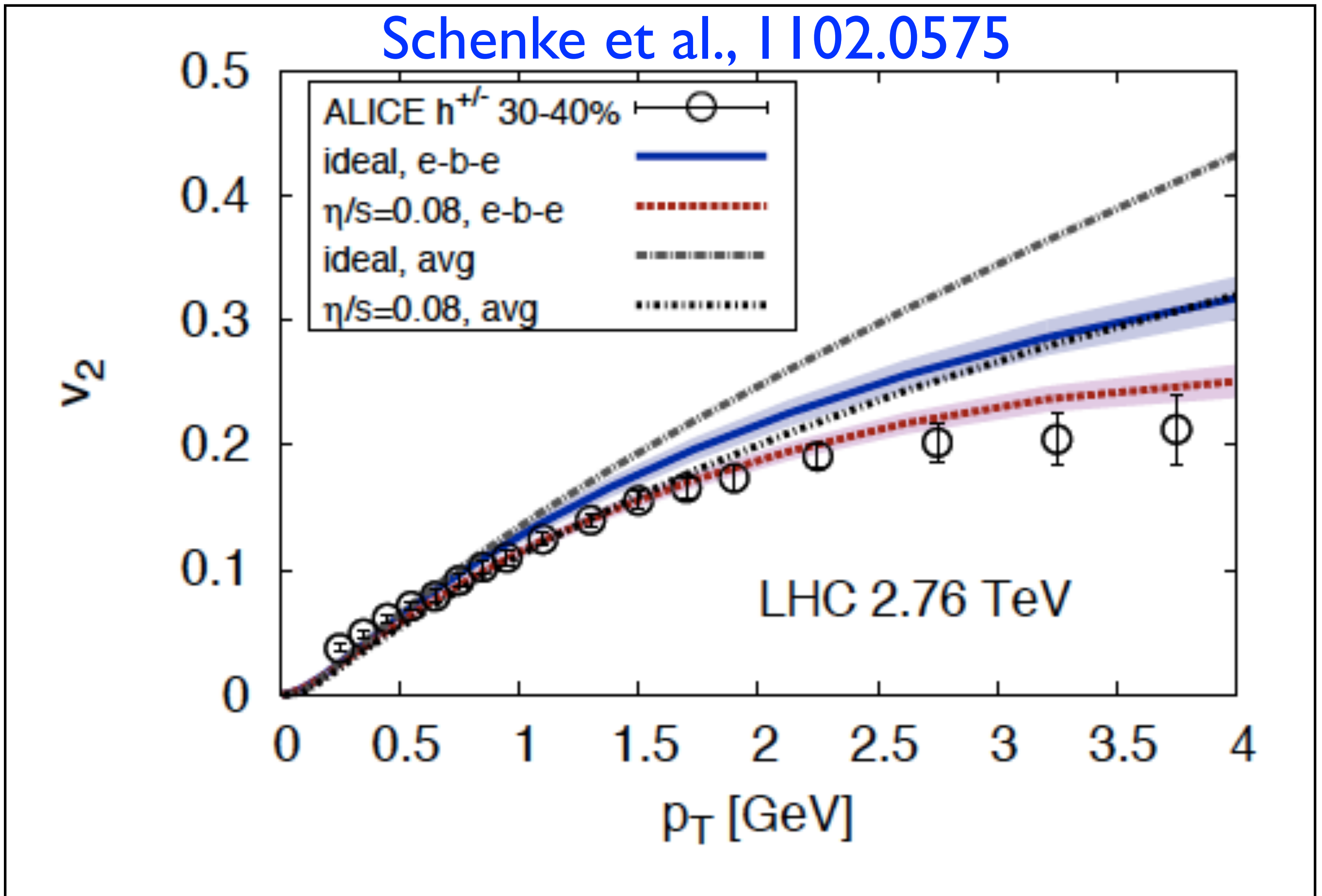


- Behavior compatible with hydro extrapolations from RHIC assuming that η is ≈ or slightly larger.
- The scQGP claims remain.
- Many things to be settled.

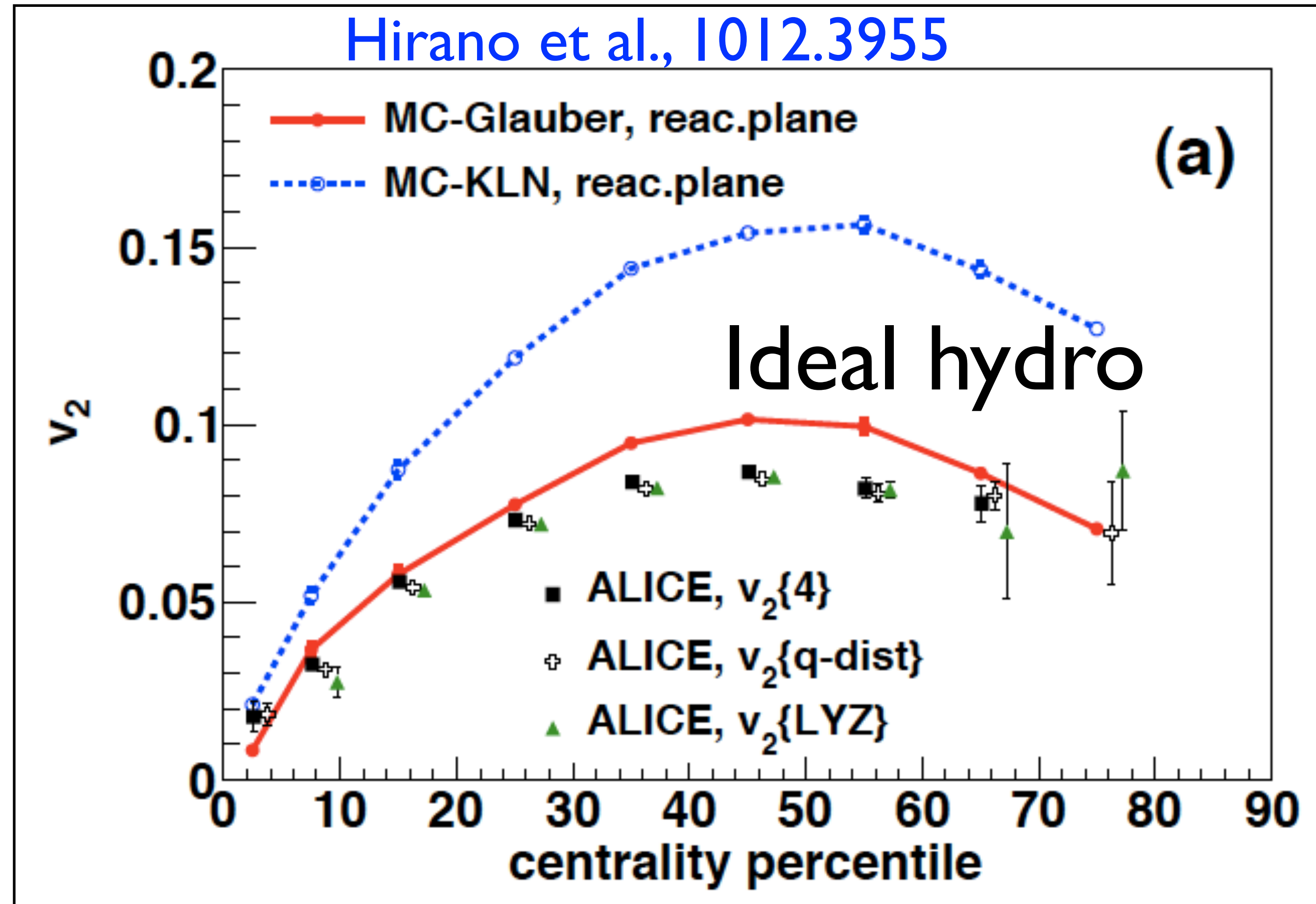


Azimuthal asymmetries:

Schenke et al., 1102.0575



Hirano et al., 1012.3955



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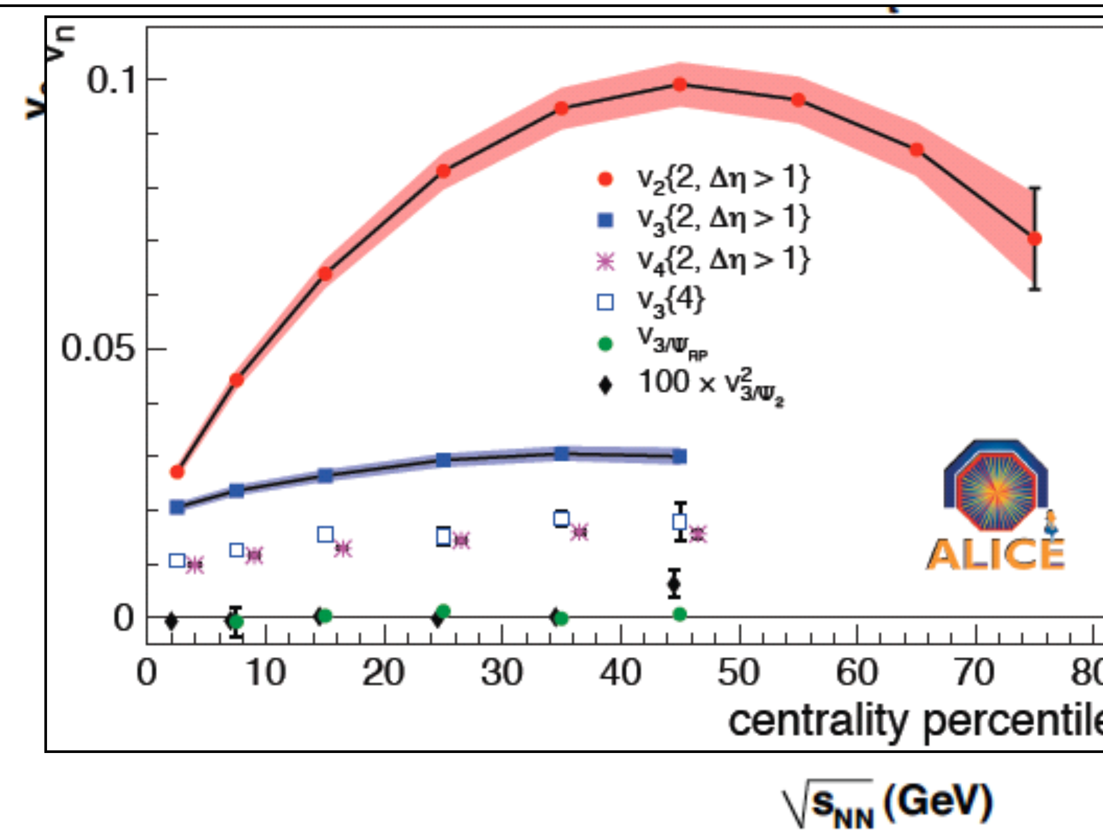

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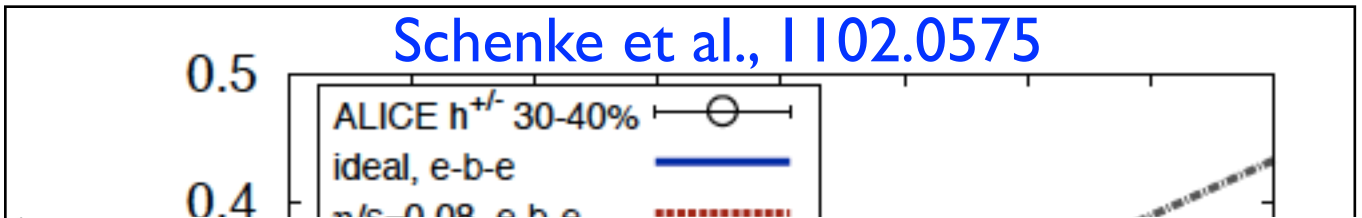
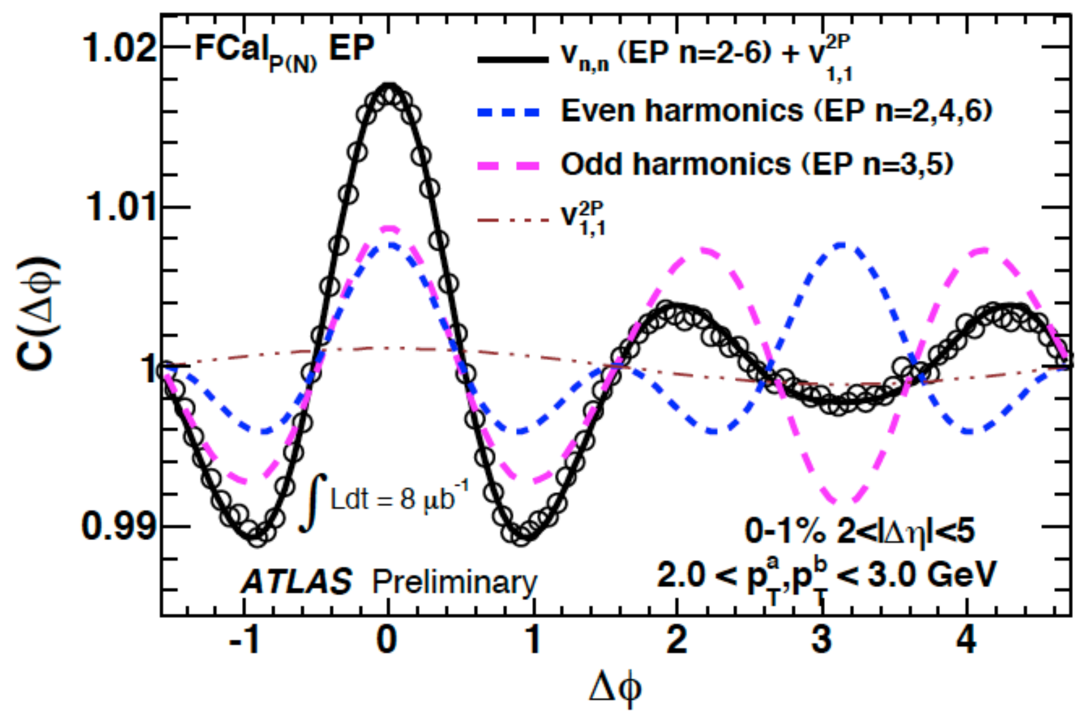
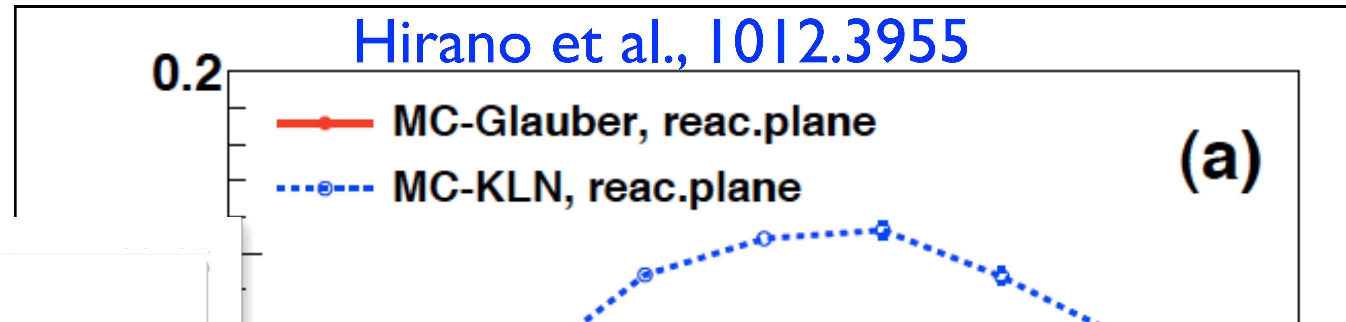


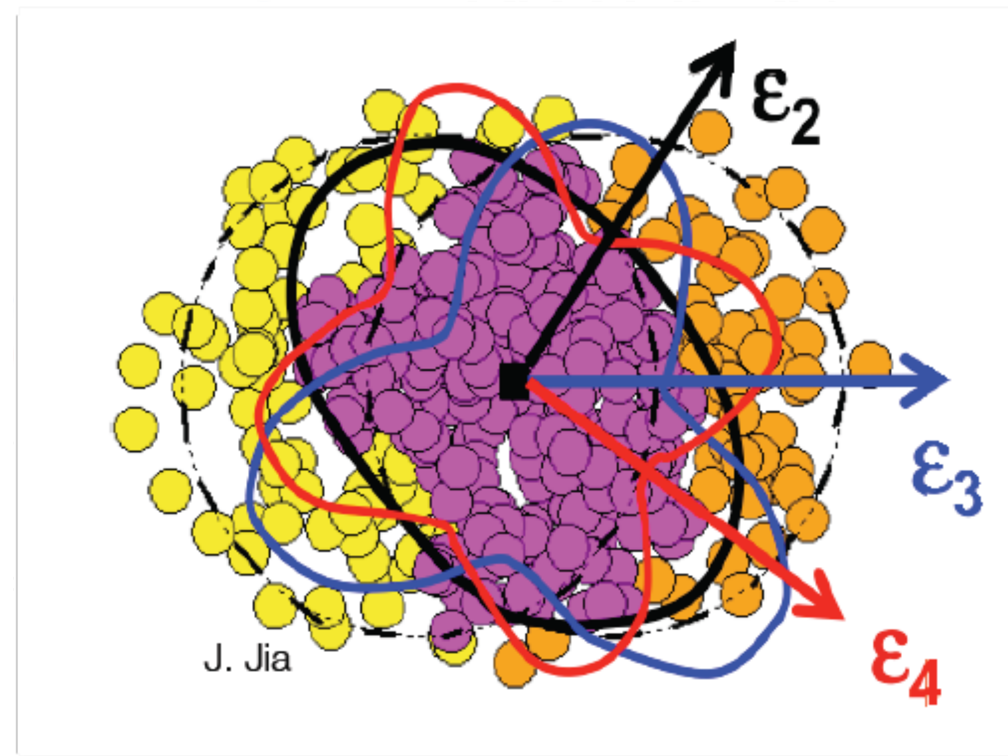


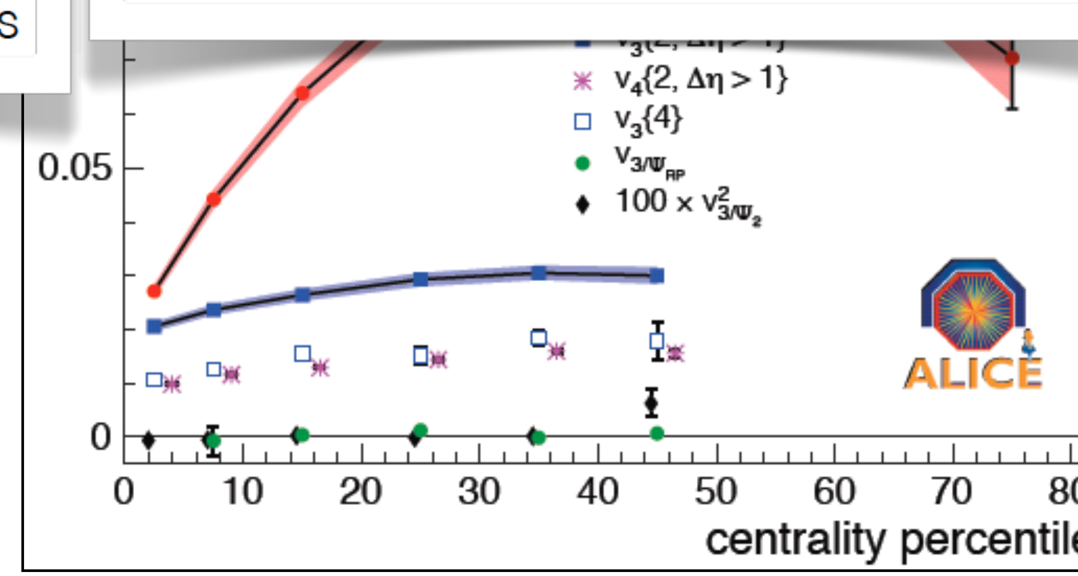
Fourier decomposition shows interplay of even and odd contributions: “ridge” and “cone” appear as consequences of global event properties

RHIC assuming that η is ≈ or slightly larger.

- The scQGP claims remain.
- Many things to be settled.

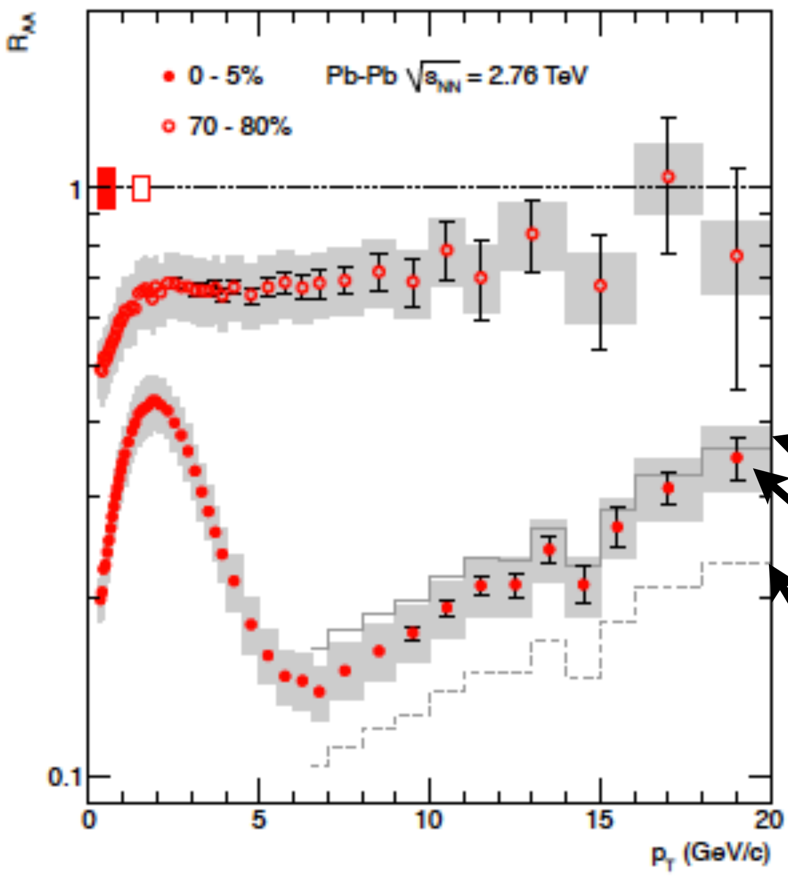




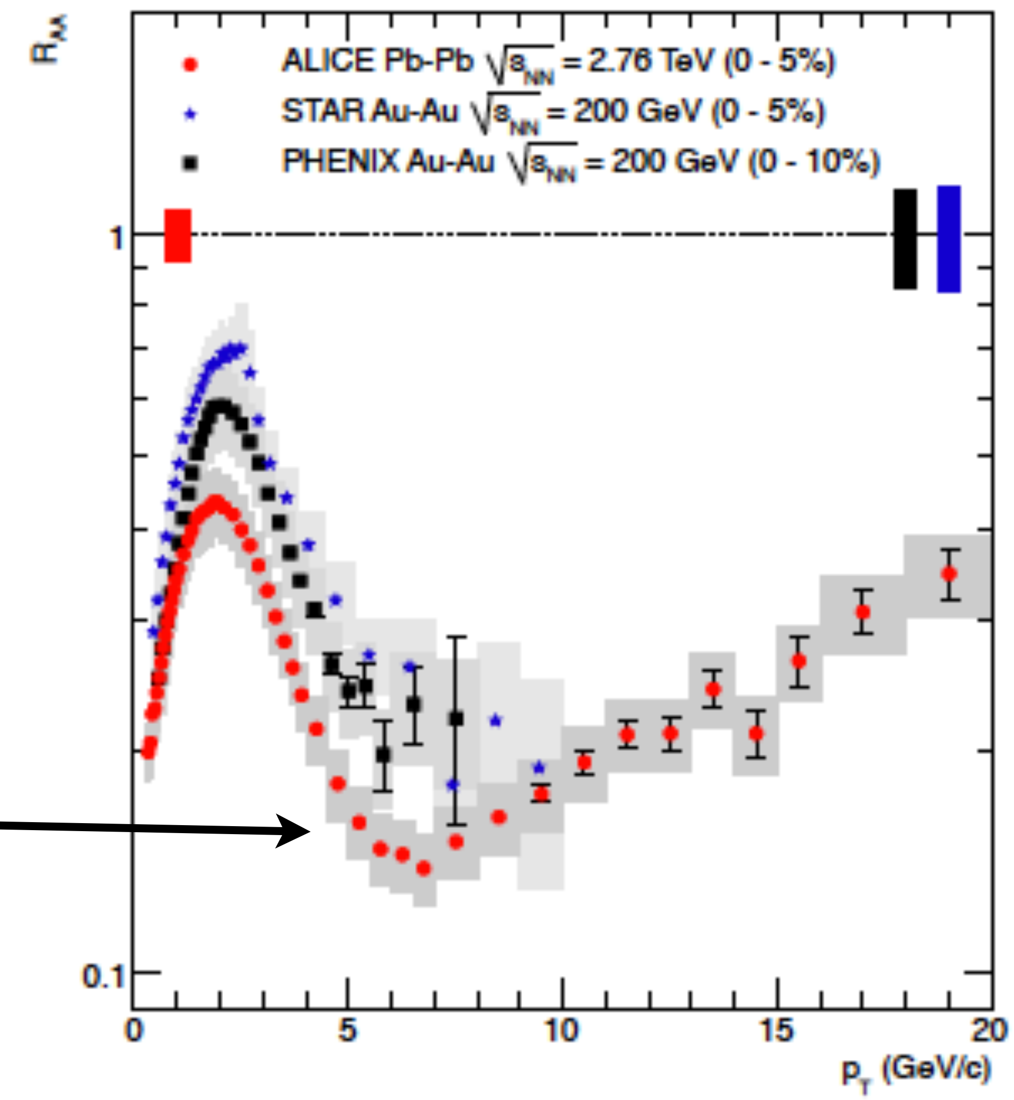


Results for R_{AA}:

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

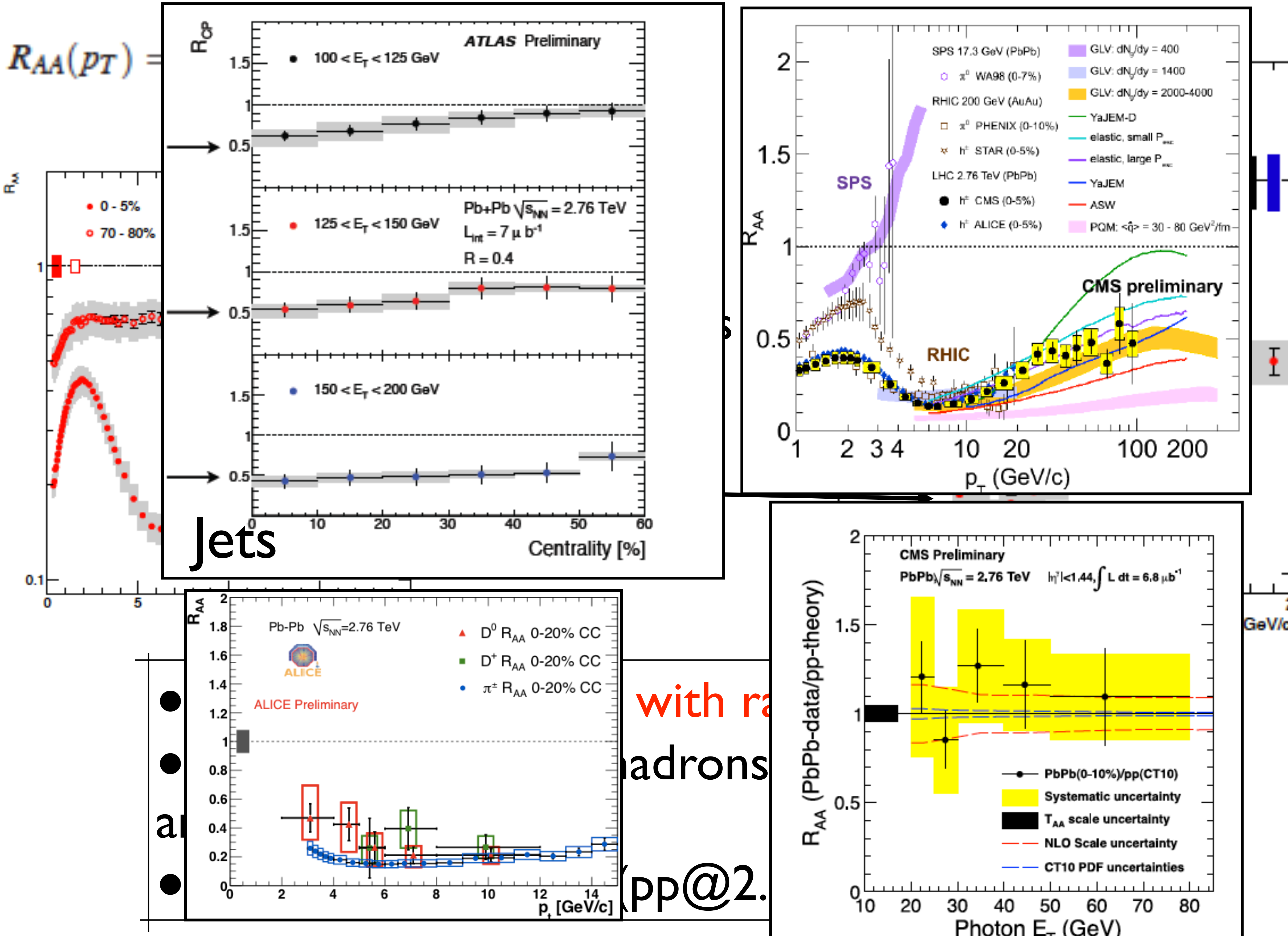


Interpolations using:
1.96 to 7
0.9 to 7
NLO QCD



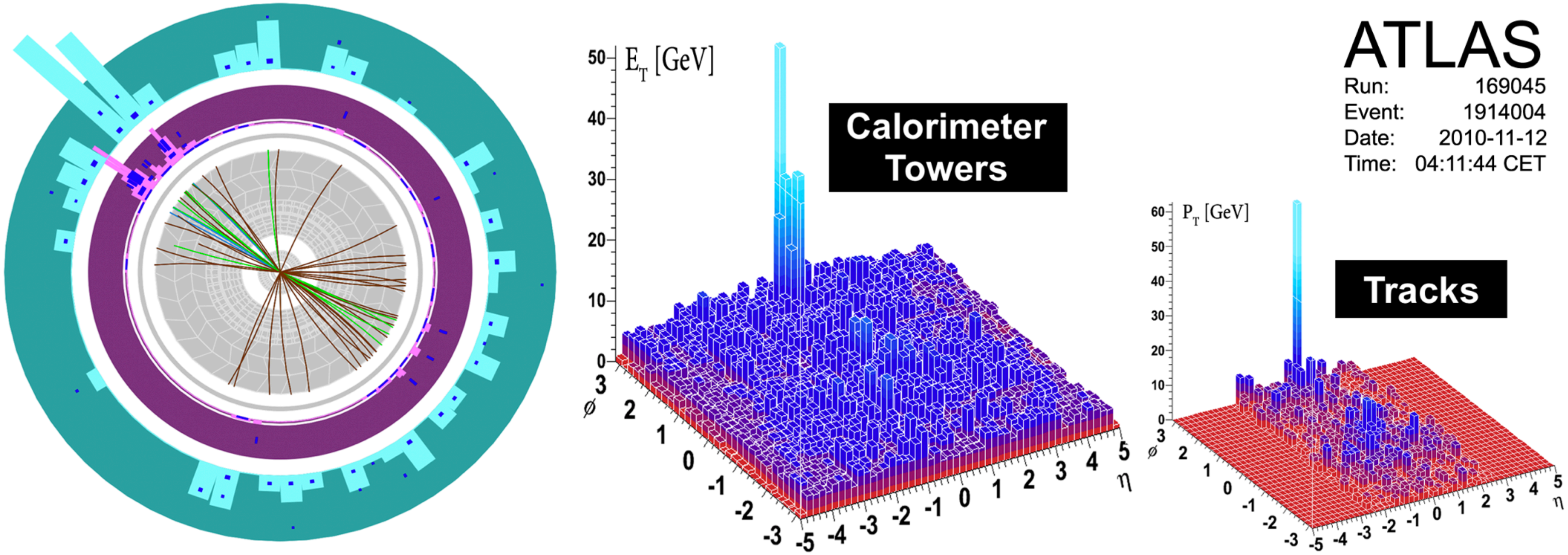
- Behavior compatible with radiative eloss.
- Similar for charged hadrons and for jets?!
- Reference crucial!!! (pp@2.76 TeV done).

Results for R_{AA}:



- ... with ra...
- ...adrons ...
  a...
- ... (pp@2. ...

LHC-specific: dijets



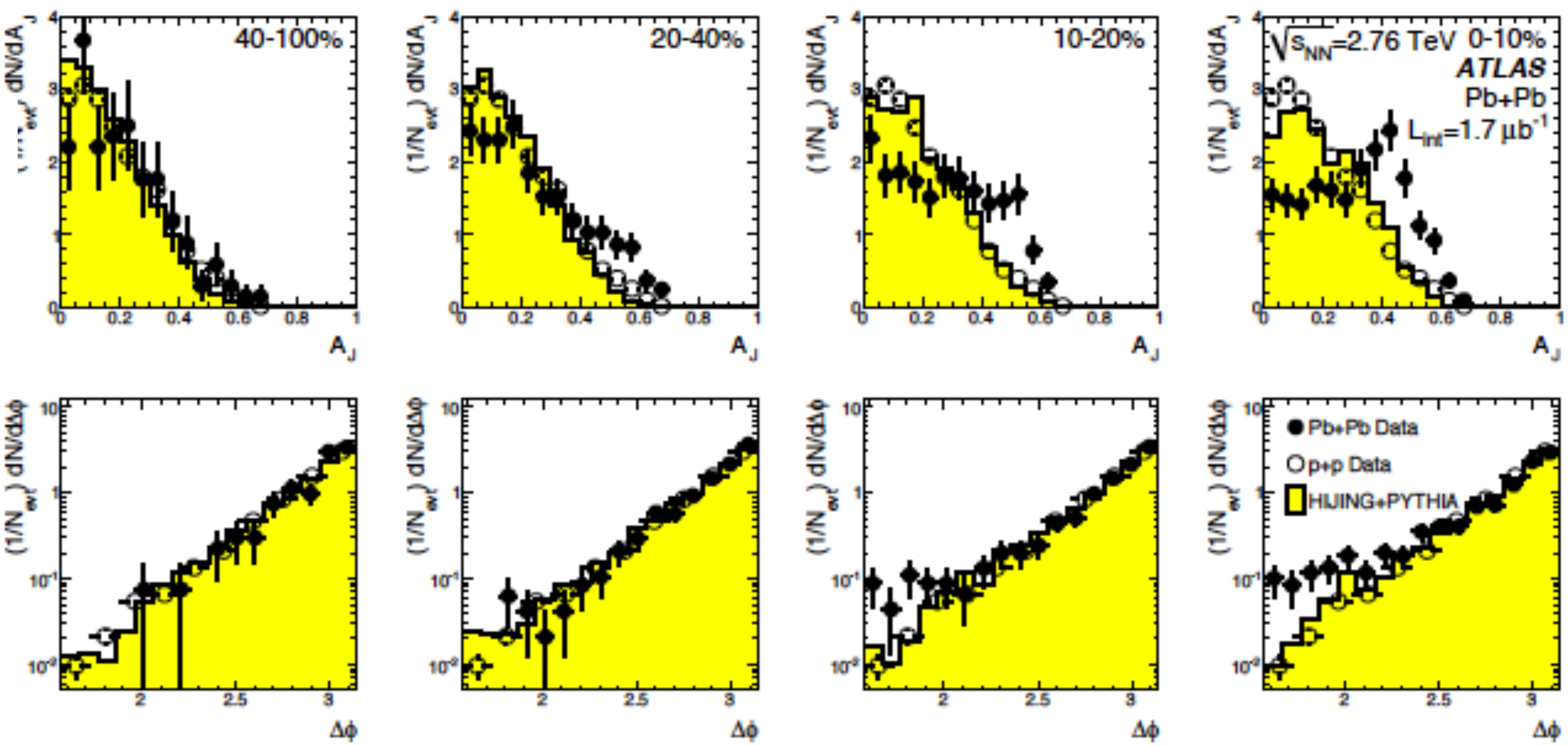
anti-k_T, D=0.4

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

$E_{T2}=E_{T1}/2 \Rightarrow$

$A_J=1/3$

- CMS got similar results, plus particles.



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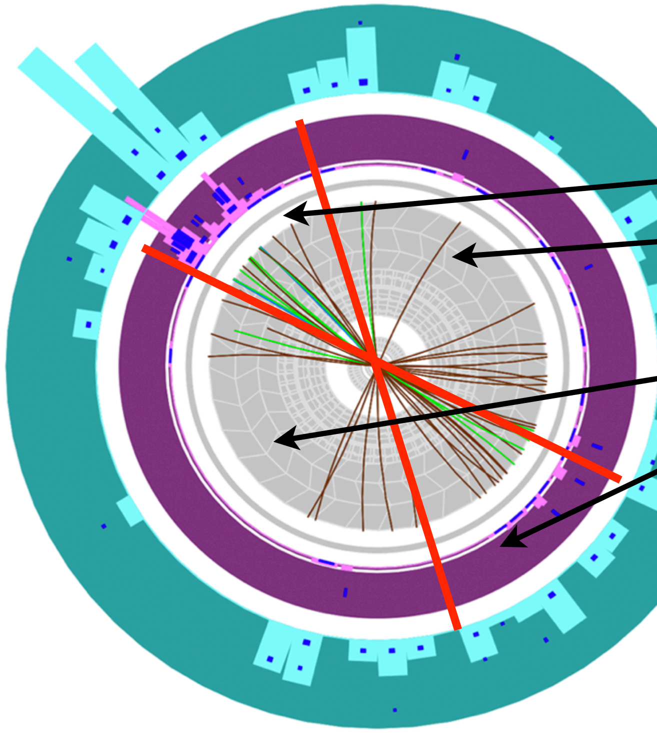

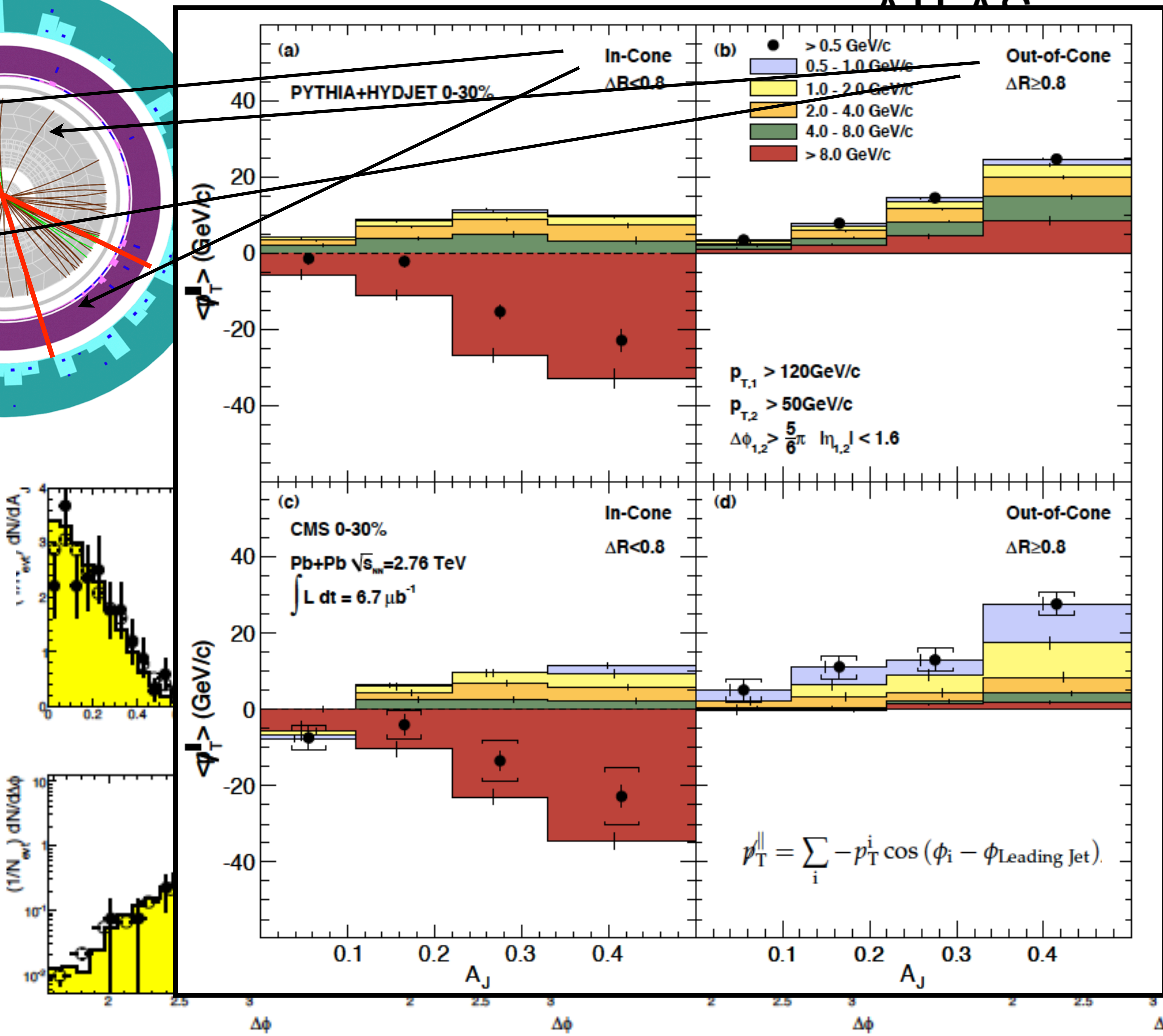

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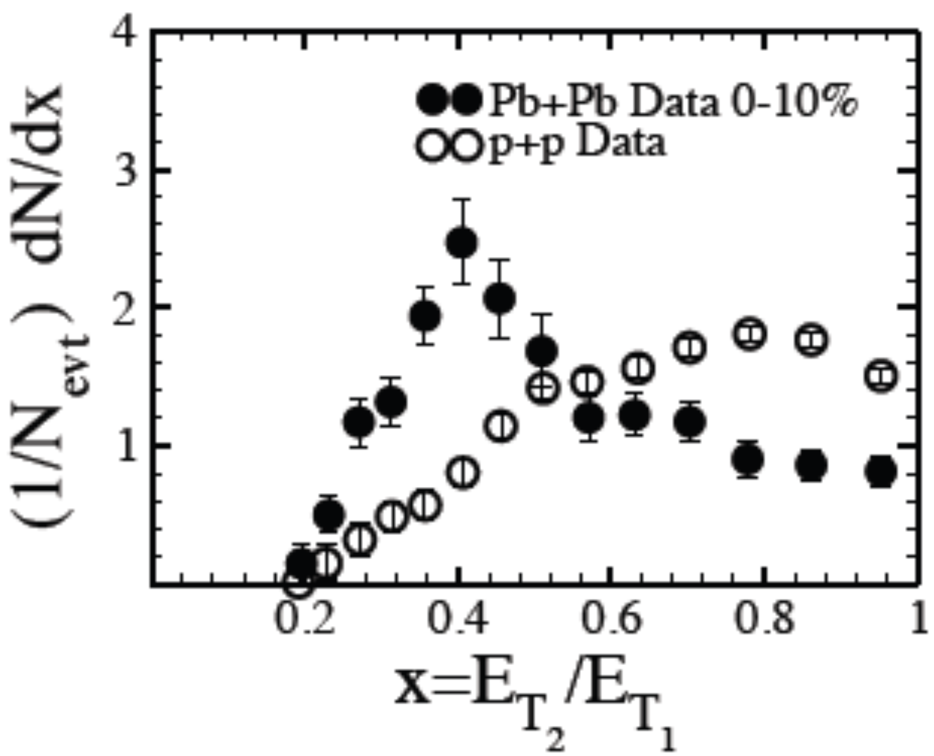
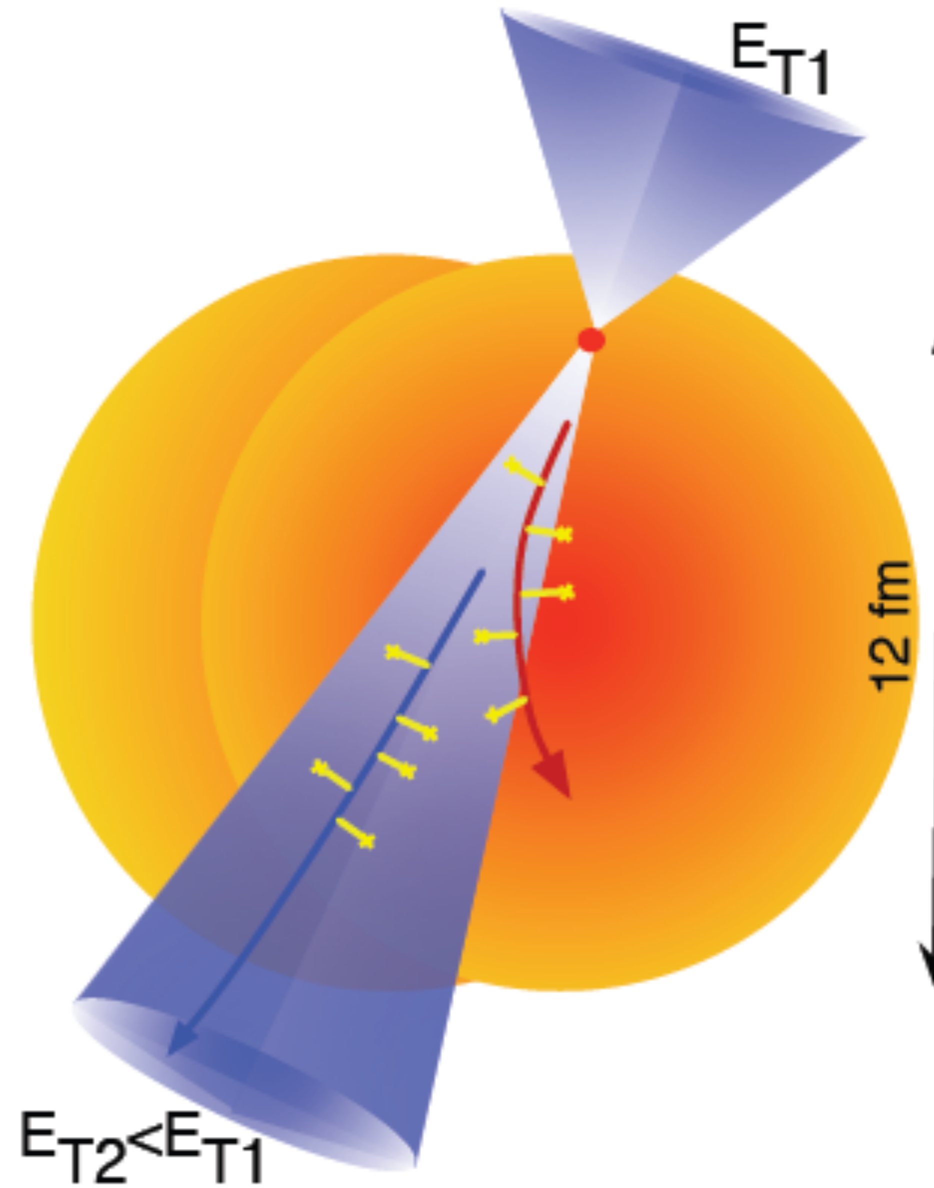
Dijets (II):

Casalderrey-Solana, Milhano, Wiedemann, 1012.0745; also Qin and Müller, 1012.5280

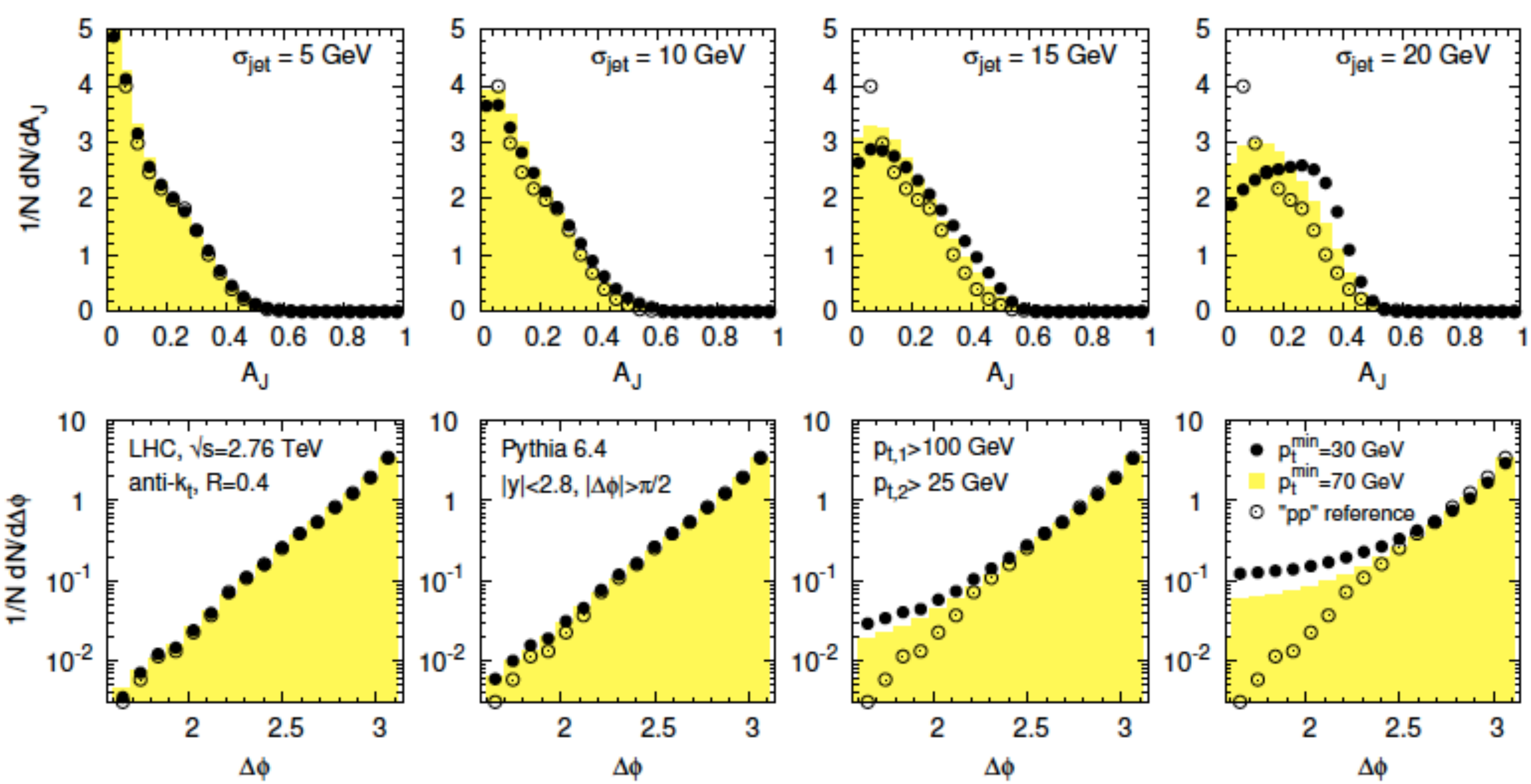




- Small kick to the gluons which go 'out-of-cone' may lead to this additional jet-energy 'degradation'.
- $E_{gluon}<\sqrt{\text{qhatL}}$ gives qhatL=50-100 GeV^2, in rough agreement with RHIC extrapolations.
- In pp there is already a lot of degradation (<x> differs ~ 10 %).

Dijets (II):

Jets are involved observables...

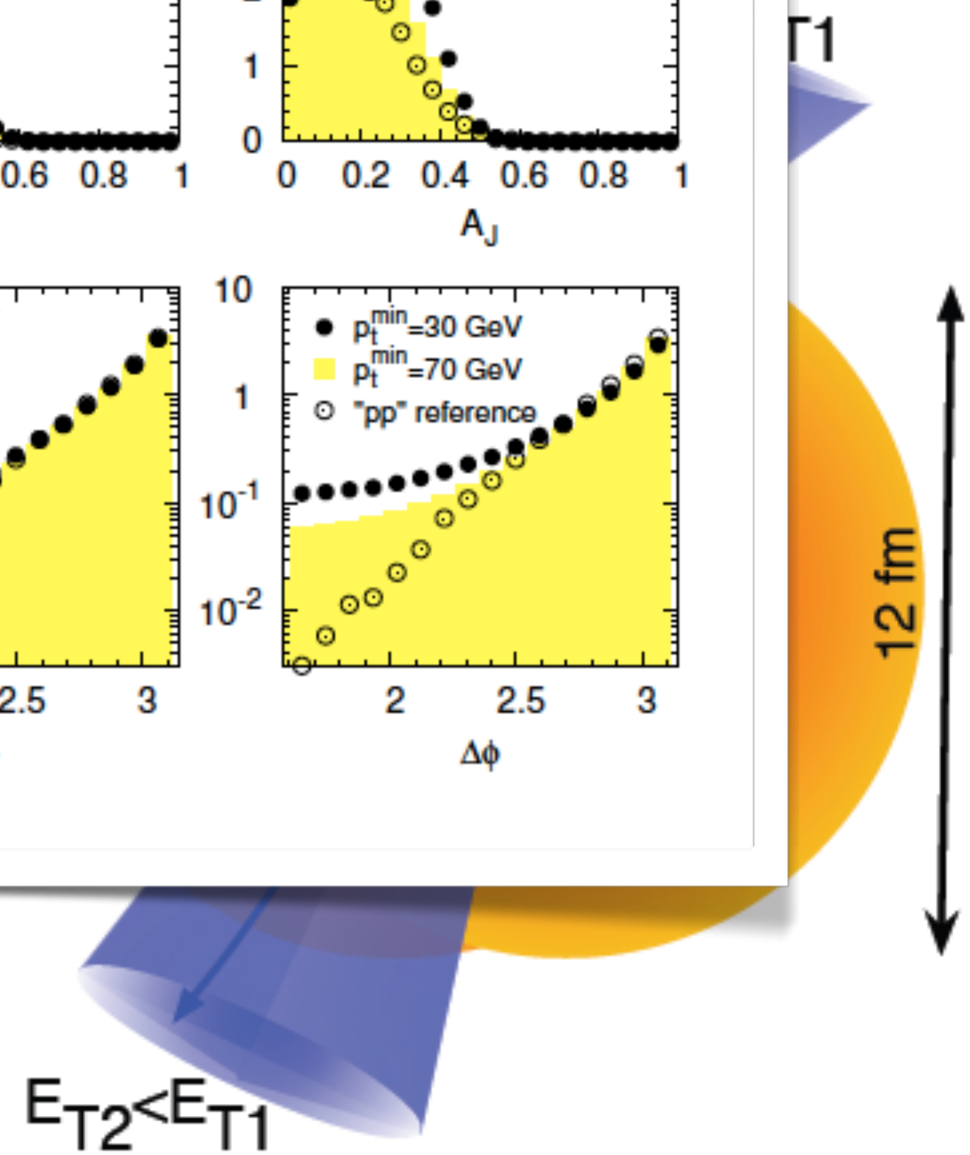


Cacciari et al., 1101.2878

no,

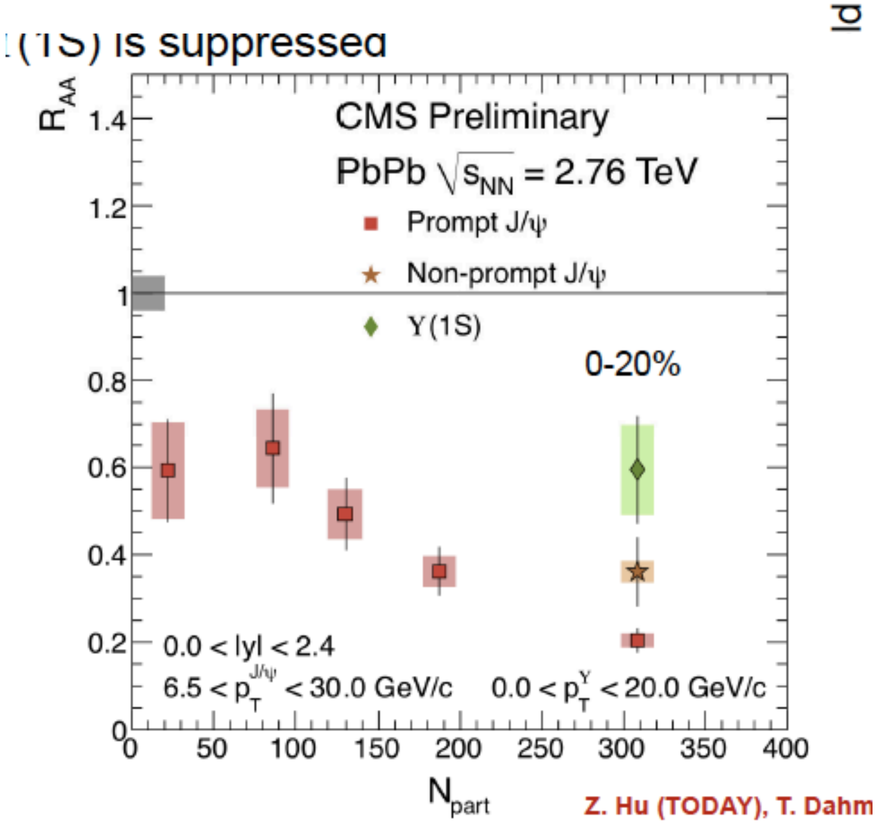
;

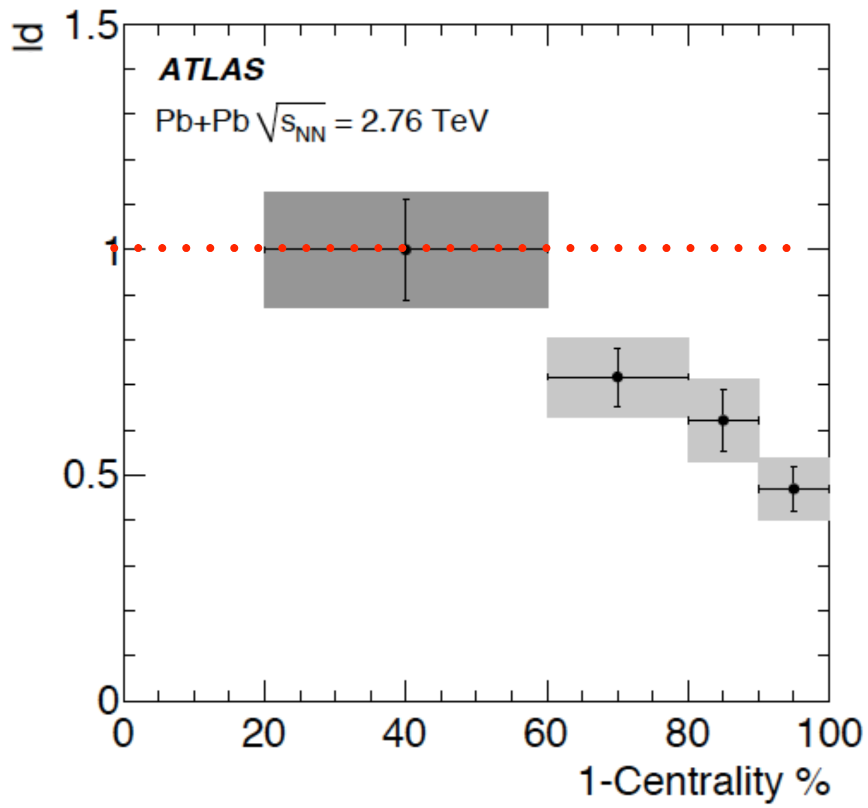
280

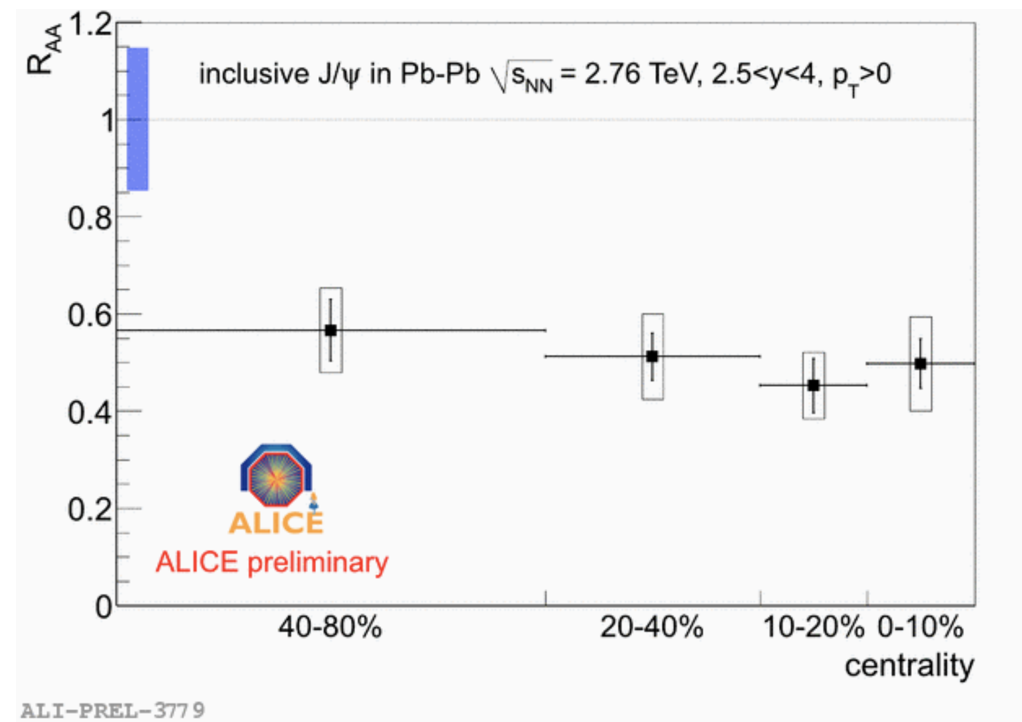


- Sl
'out
add
- E
GeV², in rough agreement with RHIC extrapolations.
- In pp there is already a lot of degradation (<x> differs ~ 10 %).

Quarkonia:



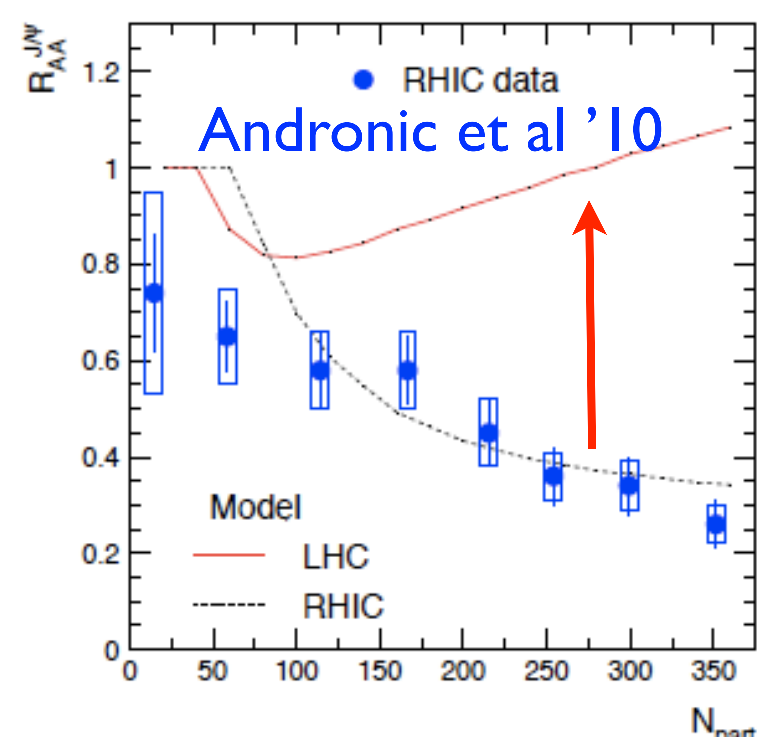




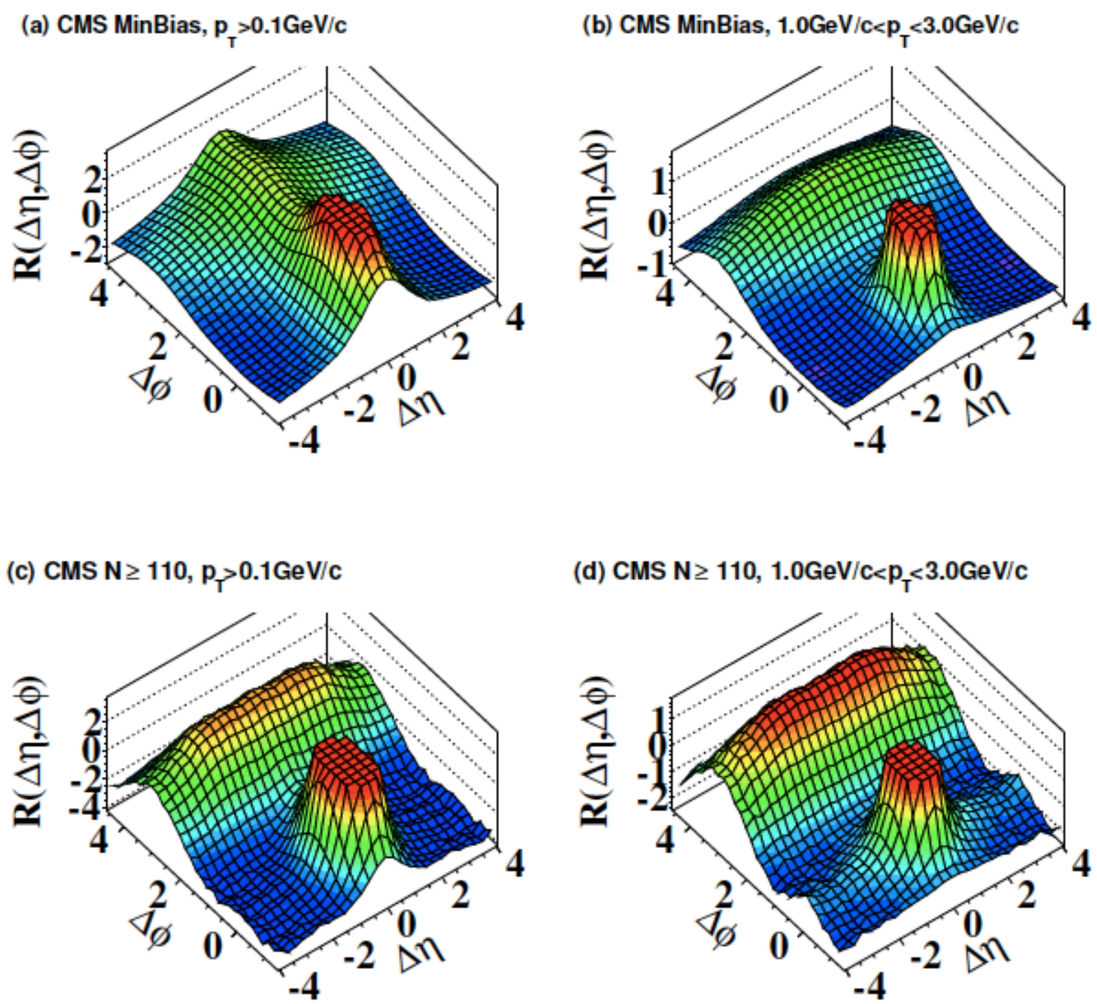
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

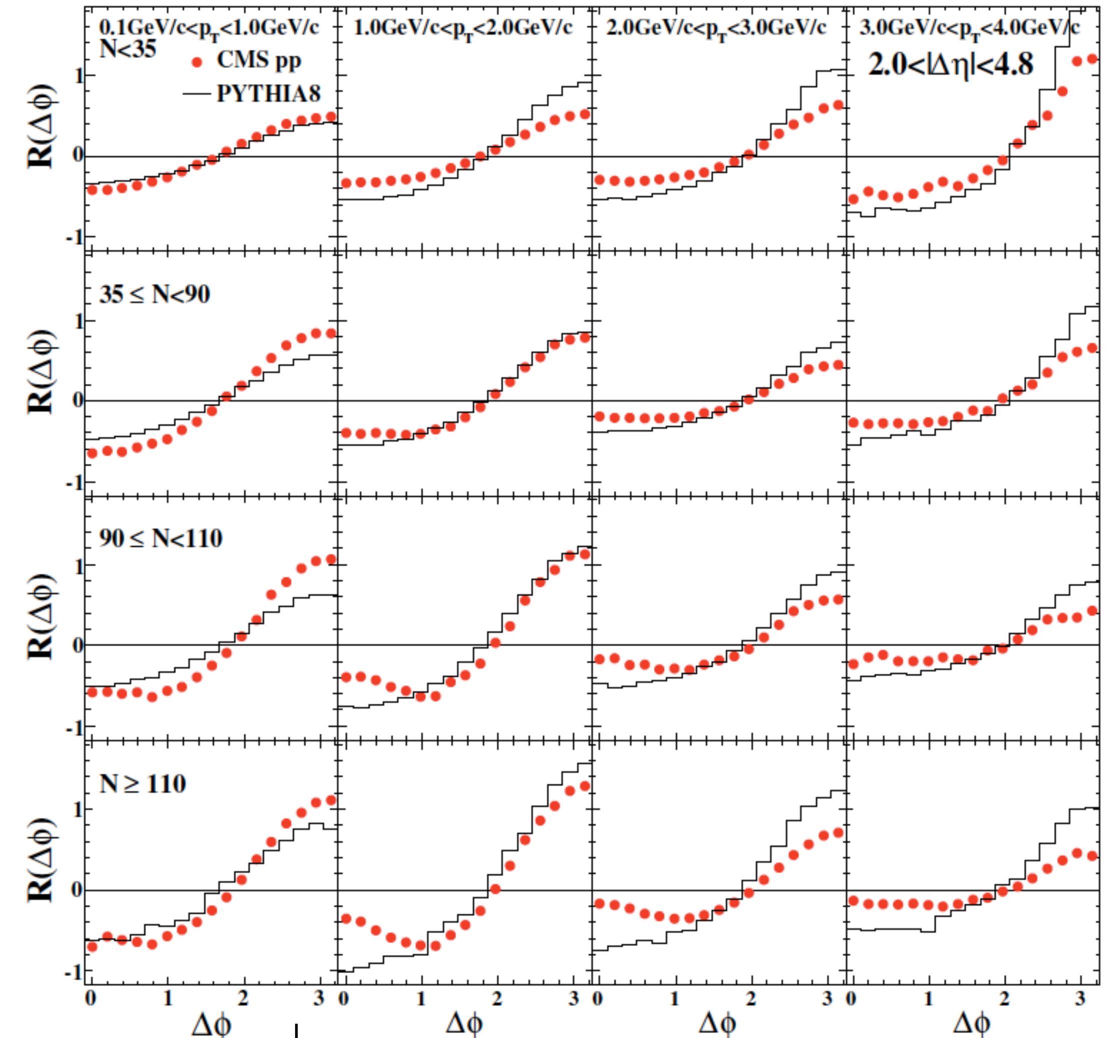
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- J/ψ results do not show enhancement.
- Higher BBbar states show larger suppression (CMS): termometer?

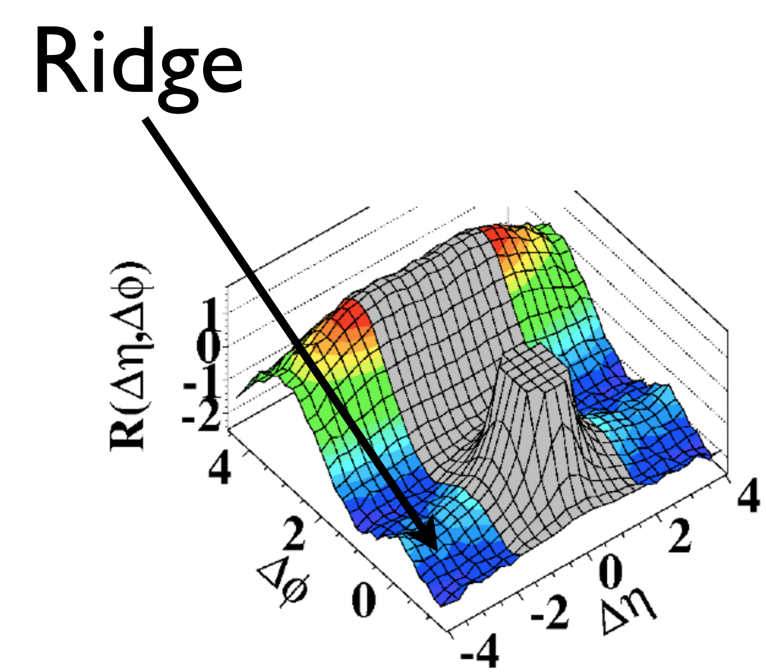


Rapidity correlations (I):

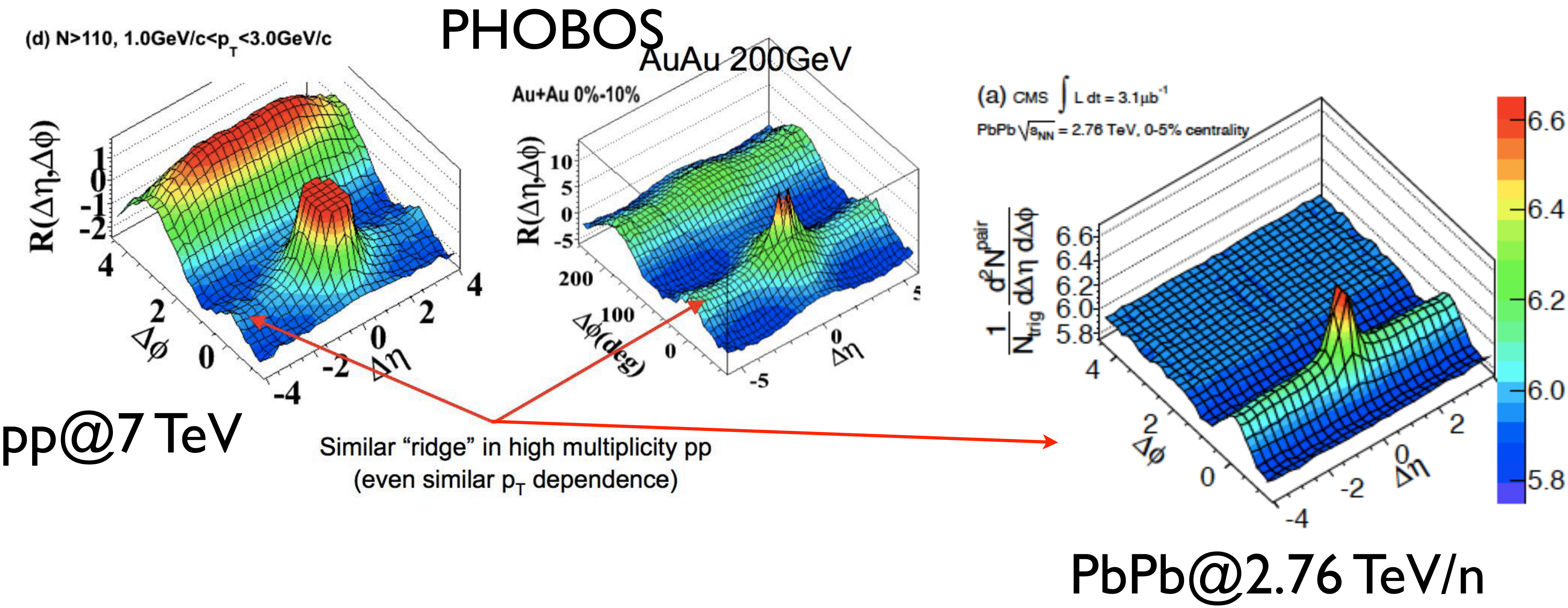




- η-elongated structure in the two-particle correlation in the near and away side regions.
- Present in high multiplicity pp@LHC (CMS, 7 TeV) and in central AuAu@RHIC and PbPb@LHC.



Rapidity correlations (II):



- Long range rapidity correlations in particle production appear naturally in several models: string models with a varying number of them, CGC,...
- Origin of the elongation in η for the ridge unsettled yet: coupling fragmentation ↔ flowing medium, ISR, flow itself (v_3),...

Summary:

Observable at RHIC	Standard interpretation	Prediction for the LHC
Low multiplicity	Strong coherence in particle production	$dN_{ch}/d\eta\|_{\eta=0}<1700$ for central collisions ✓
v_2 in agreement with ideal hydro	Almost ideal fluid	Similar or smaller $v_2(p_T)$ ✓
Strong jet quenching	Opaque medium	R_{AA}(20 GeV)~0.1-0.2 for π^0 ✓

- Quite a bit for less than 7 weeks of data taking!!!

- The very first data seem, at first sight, not to be in dispute with the claims at RHIC - the problems remain too.

- LHC offers new opportunities, both enlarging the lever arm (in energy, in p_T,...) for existing observables and offering new ones (identified heavy quarks, jets, correlations,...). Fun has just begun!!!

Summary:

Plans (tentative!?):

* PbPb @ 2.76 ATeV: four weeks at the end of 2011; at least 3 times the luminosity in 2010. End of 2012?

* pPb @ 4.4 ATeV: studies during the PbPb run in 2011, run at the end of 2012?

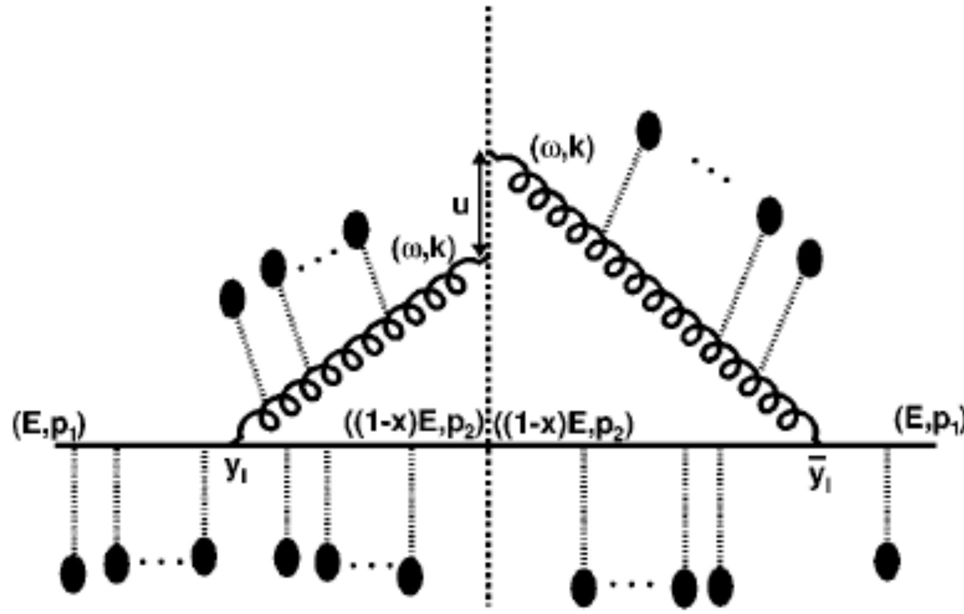
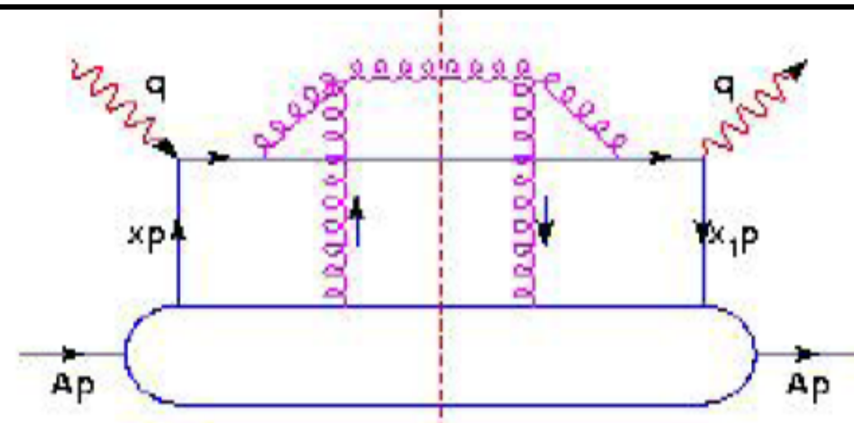
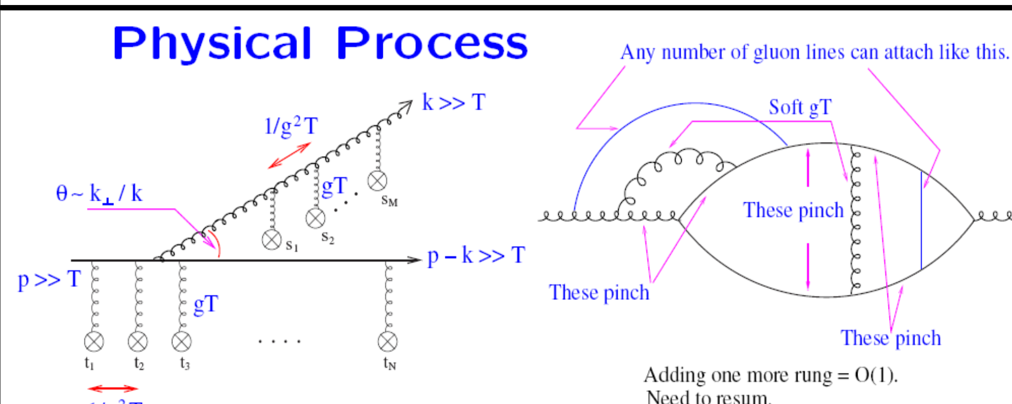
- Quite a bit for less than 7 weeks of data taking!!!

- The very first data seem, at first sight, not to be in dispute with the claims at RHIC - the problems remain too.

- LHC offers new opportunities, both enlarging the lever arm (in energy, in p_T,...) for existing observables and offering new ones (identified heavy quarks, jets, correlations,...). Fun has just begun!!!

Backup:

Model list:

Model	Diagrams	Ingredients	Parameter
ASW		Static scattering centers, Poissonian QW	qhat
GLV / WHDG(elastic)			dN_g/dy, T / α_s, T
GMW		FF in eA, modified DGLAP	<FF> or qhat, T
AMY (elastic)		HTL medium, rate eqs.	α_s, T

Embedding in a medium:

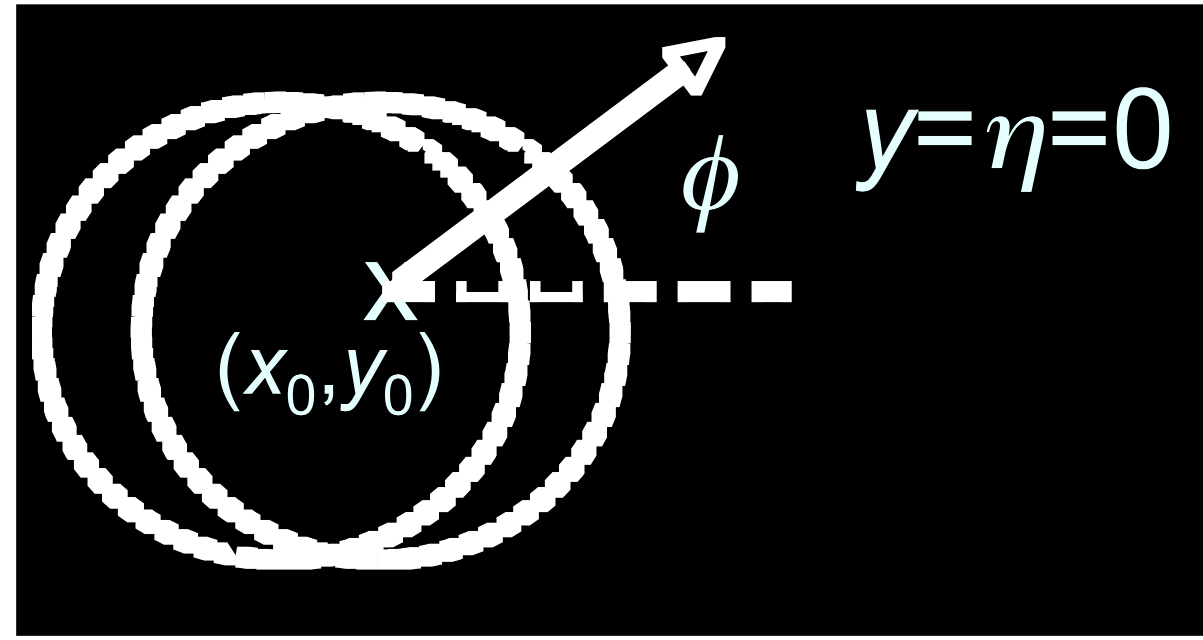
- Calculation of eloss has to be embedded in a geometry:

  * Homogeneous piece of fixed length ⇒ qhat~1 GeV^2/fm.

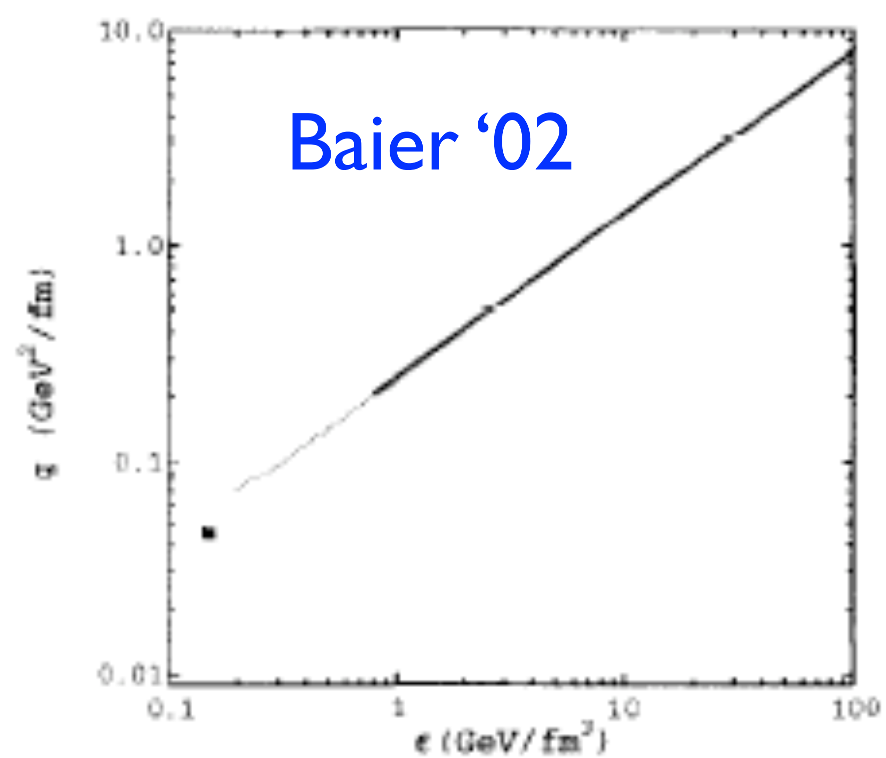
  * Density diluting as 1/τ ⇒ qhat~1 GeV^2/fm.

  * Medium as overlap (N_{coll}), $T_A(s)T_B(b\text{-}s)$ ⇒ qhat~10 GeV^2/fm.

  * Hydrodynamical medium ⇒ K~2-4.



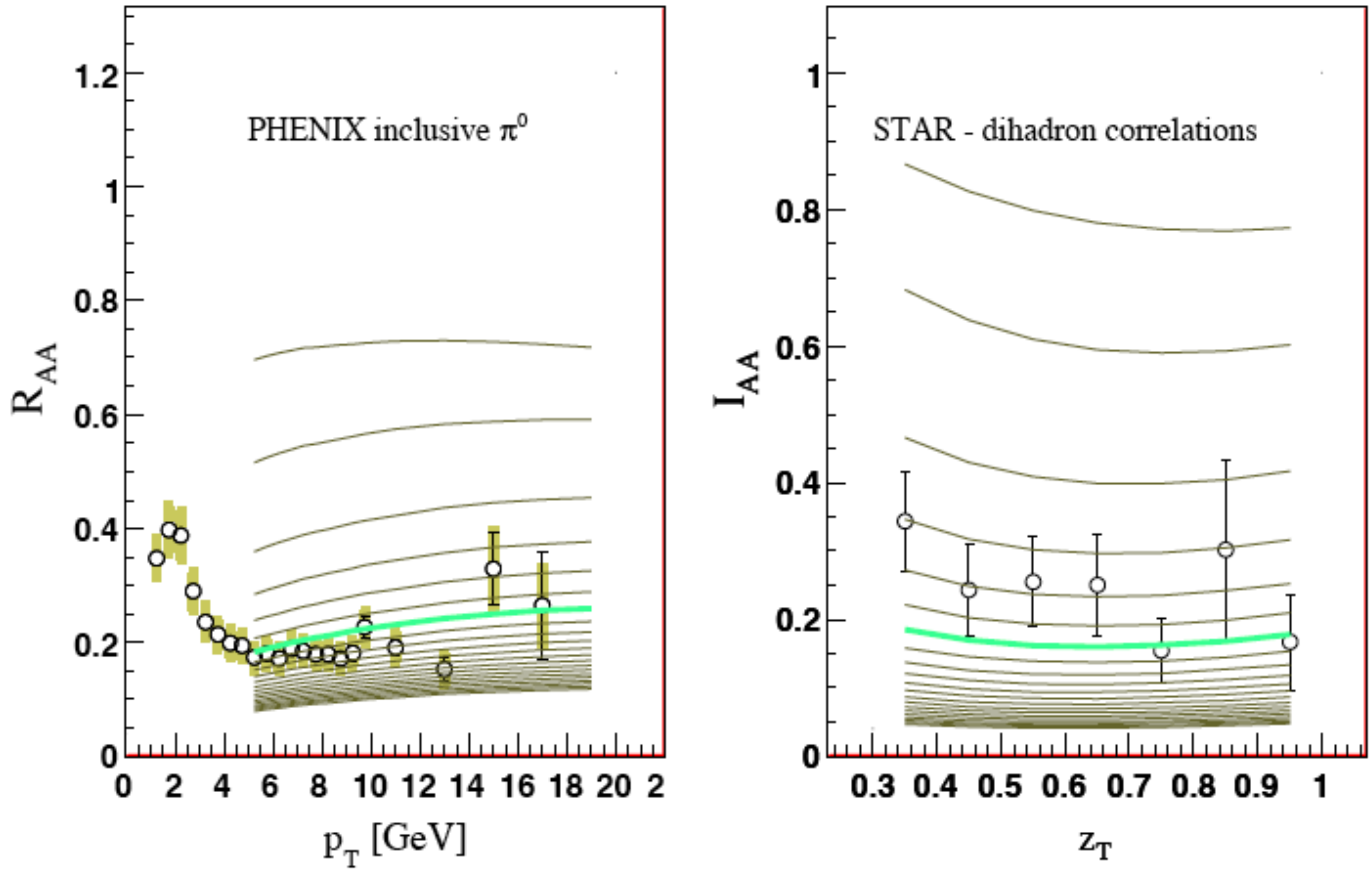
$$\hat{q}(\xi) = K\hat{q}_{QGP} \simeq K \cdot 2e^{3/4}(\xi)$$



Note: production points sampled as N_{coll} or N_{part}.

Radiative eloss: light hadrons (II)

NA et al '09



Radiative eloss: light hadrons (II)

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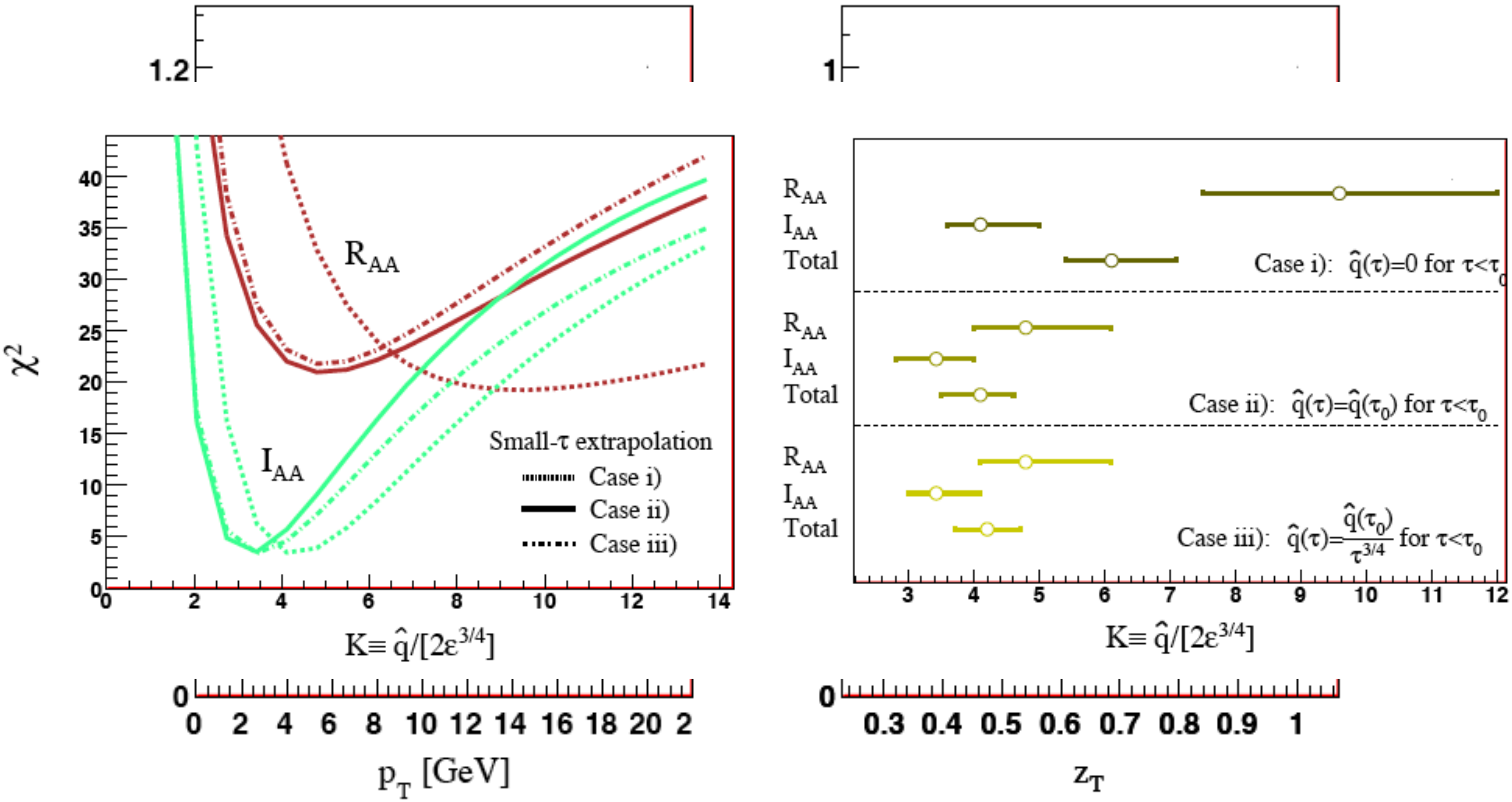


Radiative eloss: limitations

- The extracted value of qhat depends on medium model $1 < \hat{q} < 15$ GeV^2/fm ⇒ interface with realistic medium.

- Calculations done in the high-energy approximation: only soft emissions energy-momentum conservation imposed a posteriori ⇒ Monte Carlo.

- Multiple gluon emission: Quenching Weights independent (Poissonian) gluon emission: assumption! ⇒ Monte Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

- No role of virtuality in medium emissions; medium and vacuum treated differently ⇒ modified DGLAP evolution.

Radiative eloss: limitations

- The extracted value of qhat depends on medium model 1<qhat<15 GeV^2/fm ⇒ interface with realistic medium.

- Calculat ... ly soft emissions ... osteriori ⇒ Monte Ca

$$\omega \frac{dI}{d\omega} = \int_0^{k_T^{2,max}} dk_T^2\, \omega \frac{dI}{d\omega dk_T^2}\,, \quad \Delta E = \int_0^E d\omega\, \omega \frac{dI}{d\omega}$$

$$P(\Delta E) = \omega \frac{dI}{d\omega} = \int_0^{k_T^{2,max}} dk_T^2\, \omega \frac{dI}{d\omega dk_T^2}\,, \quad \Delta E = \int_0^E d\omega\, \omega \frac{dI}{d\omega}$$

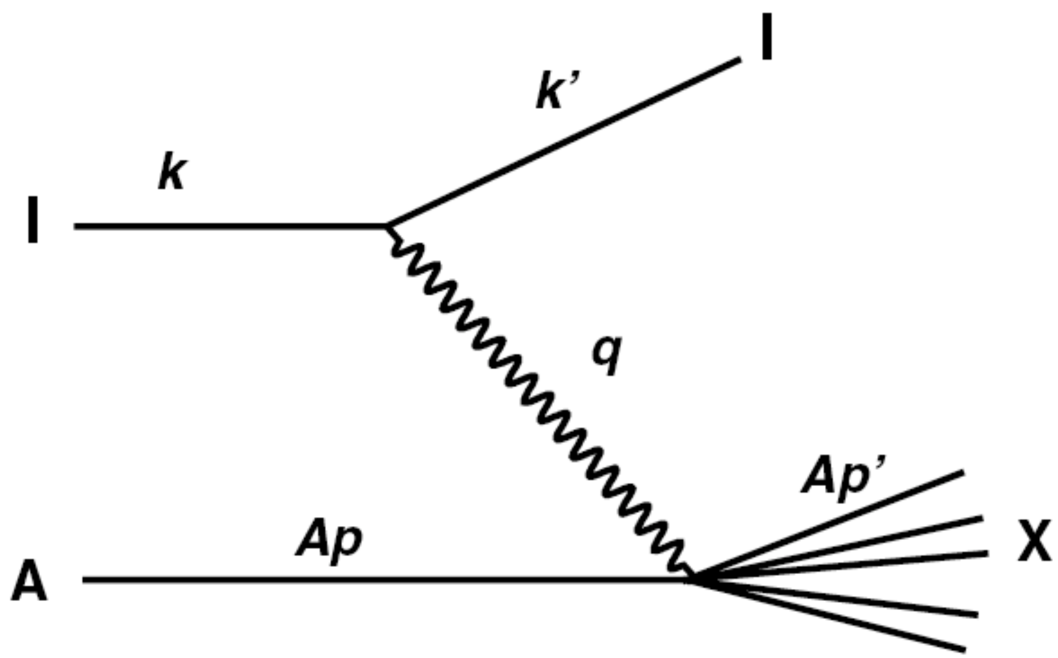
- Multip ... (Poisson ... PQM, PYQU

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta \left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[- \int d\omega \frac{dI}{d\omega} \right]$$

$$P_{trunc}(\Delta E) = p_0 \delta(\Delta E) + P_{cont}(\Delta E)\Theta(E - \Delta E) + \delta(E - \Delta E) \int_E^{\infty} d\epsilon P(\epsilon)$$

- No role of virtuality in medium emissions, medium and vacuum treated differently ⇒ modified DGLAP evolution.

DIS:



$$F_2^A(x, Q^2) = \frac{Q^2(1-x)}{4\pi^2\alpha_{EM}}\sigma_{\gamma^*\text{-}A}$$

Q^2 is the transverse resolution.

x is the momentum fraction (IMF).

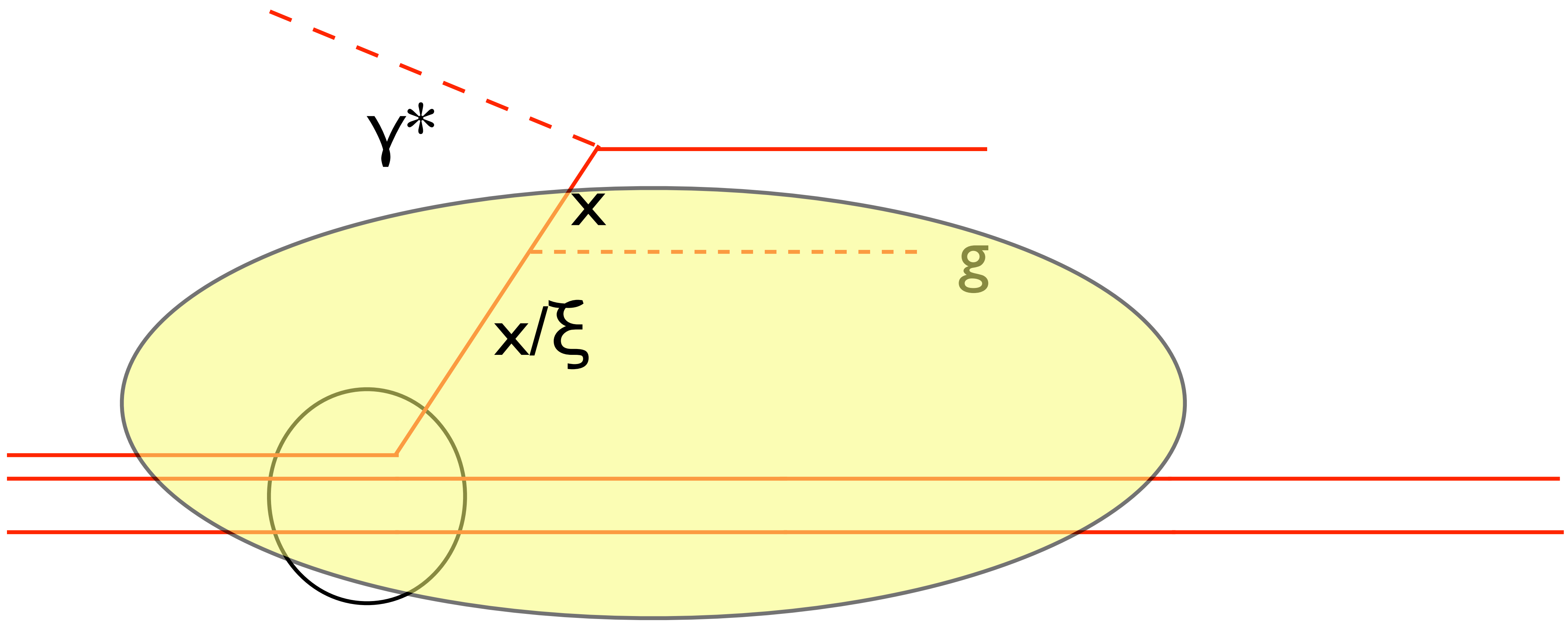
$F_2(x, Q^2)=\sum e_q^2 xq(x, Q^2)$ at LO.

$$l(k) + A(Ap) \longrightarrow l(k') + X(Ap'), \qquad Q^2 = -q^2 > 0$$

$$q = k - k', \qquad W^2 = (q+p)^2, \qquad x = \frac{-q^2}{2p\cdot q} = \frac{-q^2}{W^2 - q^2 - m^2_{\text{nucleon}}},$$

- $F_{2(1)}(x, Q^2)= F_{2(1)}(x)$ at large Q^2: Bjorken scaling, point-like partons.
- $F_2(x)=2xF_1(x)$: Callan-Gross relation, spin 1/2 quarks.
- I will be interested in small x i.e. large energies W.

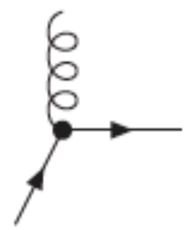
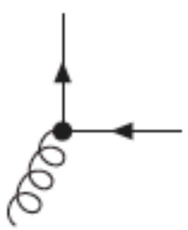
DGLAP:



At LO

$$Q^2\partial_{Q^2}\begin{pmatrix} q_i(x,Q^2) \\ \bar{q}_i(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{d\xi}{\xi}\begin{pmatrix} P_{q_iq_j}\left(\frac{x}{\xi}\right) & 0 & P_{q_ig}\left(\frac{x}{\xi}\right) \\ 0 & P_{q_iq_j}\left(\frac{x}{\xi}\right) & P_{q_ig}\left(\frac{x}{\xi}\right) \\ P_{gq}\left(\frac{x}{\xi}\right) & P_{gq}\left(\frac{x}{\xi}\right) & P_{gg}\left(\frac{x}{\xi}\right) \end{pmatrix}\begin{pmatrix} q_j(x,Q^2) \\ \bar{q}_j(x,Q^2) \\ g(x,Q^2) \end{pmatrix}$$

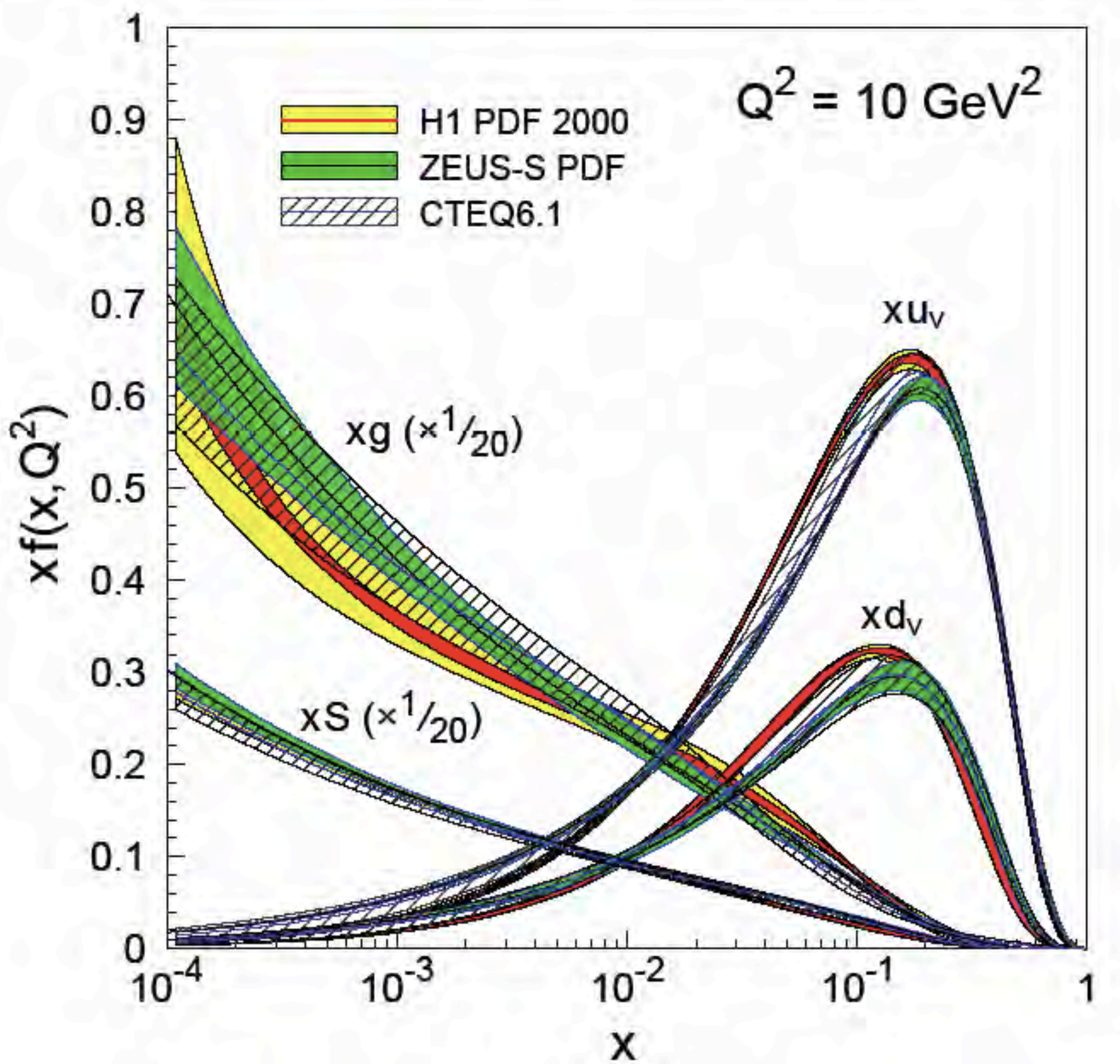
DGLAP:

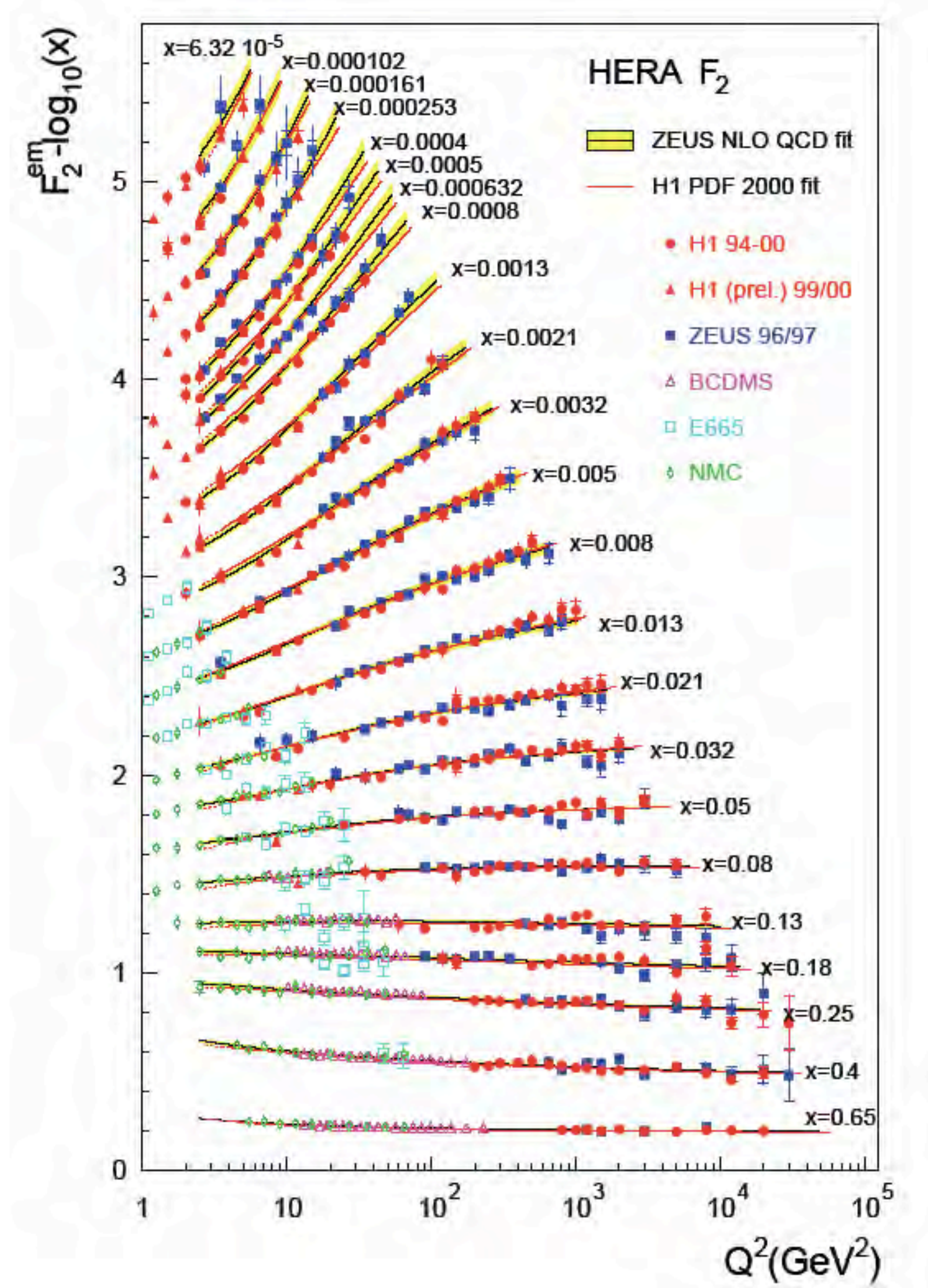
Diagram	Splitting
	$P_{qq} = C_F \left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x) \right]$
	$P_{gq} = C_F \left[\frac{1+(1-x)^2}{x} \right]$
	$P_{qg} = T_R \left[x^2 + (1-x)^2 \right]$
	$P_{gg} = 2C_A \left[\frac{x}{(1-x)_+} + (1-x)\left(x + \frac{1}{x}\right) \right] + \frac{11C_A - 4n_f T_R}{6}\delta(1-x)$

At LO

$$Q^2 \partial_{Q^2} \begin{pmatrix} q_i(x,Q^2) \\ \bar{q}_i(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j}\left(\frac{x}{\xi}\right) & 0 & P_{q_i g}\left(\frac{x}{\xi}\right) \\ 0 & P_{q_i q_j}\left(\frac{x}{\xi}\right) & P_{q_i g}\left(\frac{x}{\xi}\right) \\ P_{gq}\left(\frac{x}{\xi}\right) & P_{gq}\left(\frac{x}{\xi}\right) & P_{gg}\left(\frac{x}{\xi}\right) \end{pmatrix} \begin{pmatrix} q_j(x,Q^2) \\ \bar{q}_j(x,Q^2) \\ g(x,Q^2) \end{pmatrix}$$

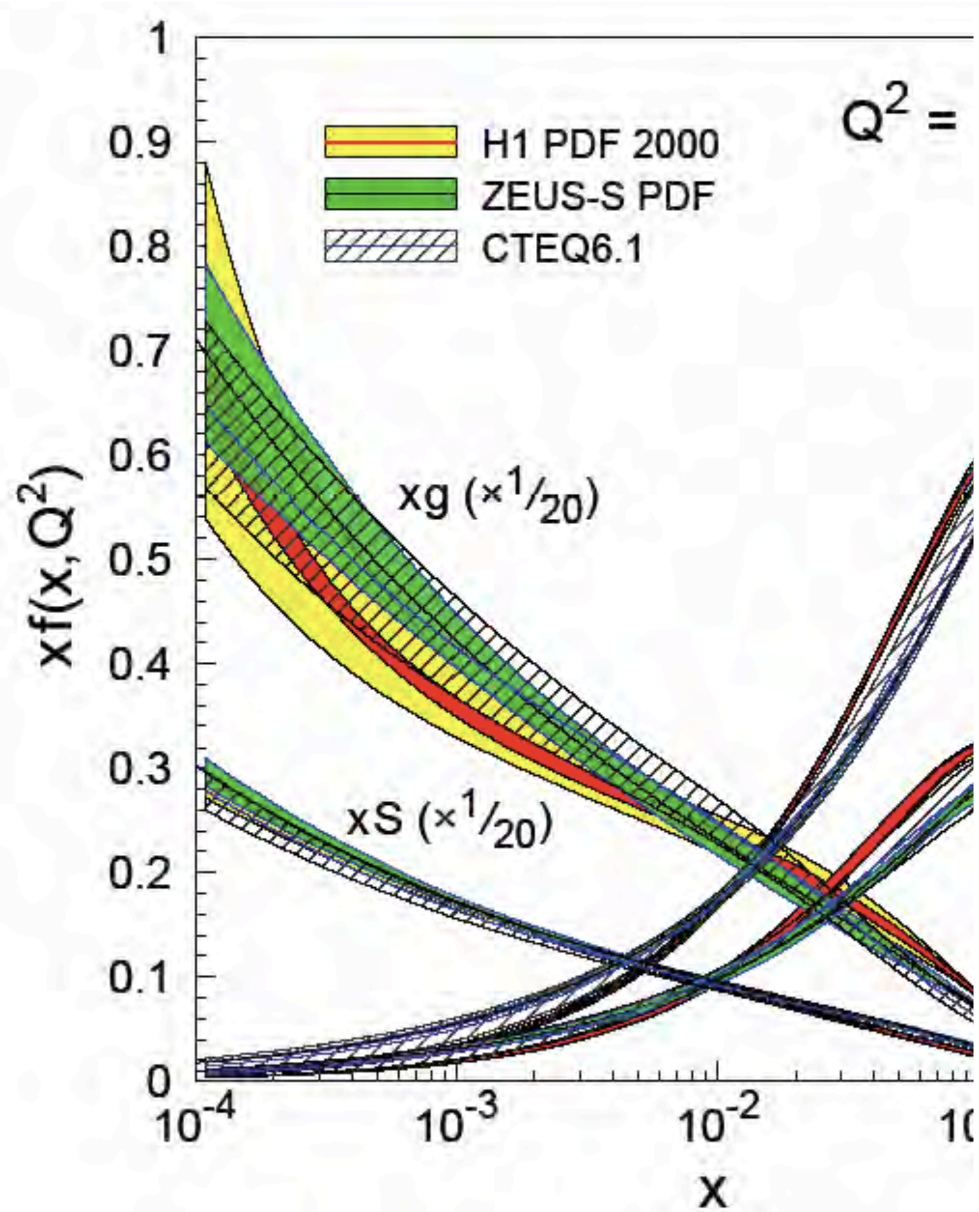
Data on the proton:

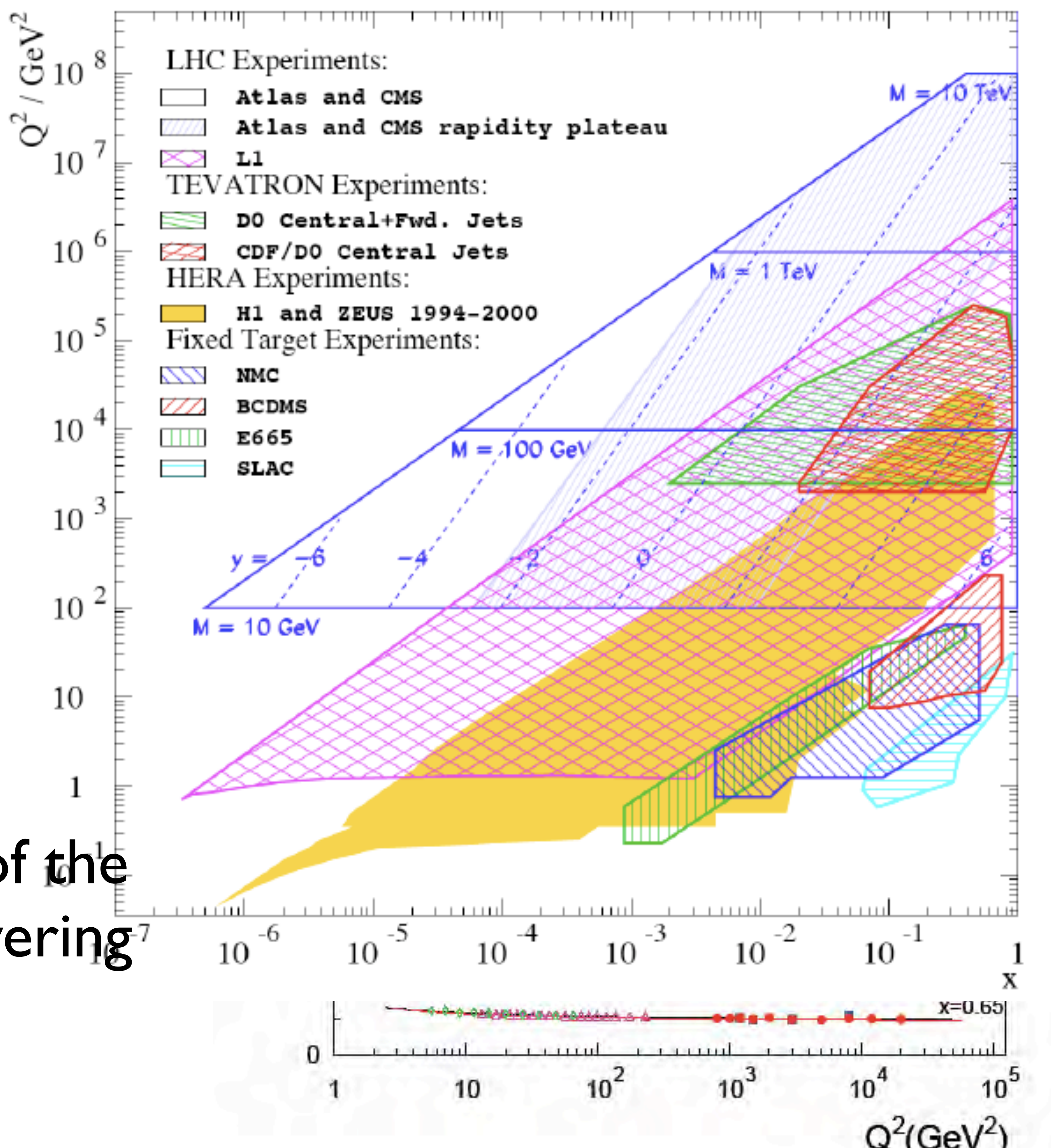




- HERA provides most of the available information, covering a large part of what is required for the LHC.

Data on the proton:





- HERA provides most of the available information, covering a large part of what is required for the LHC.

Global fits:

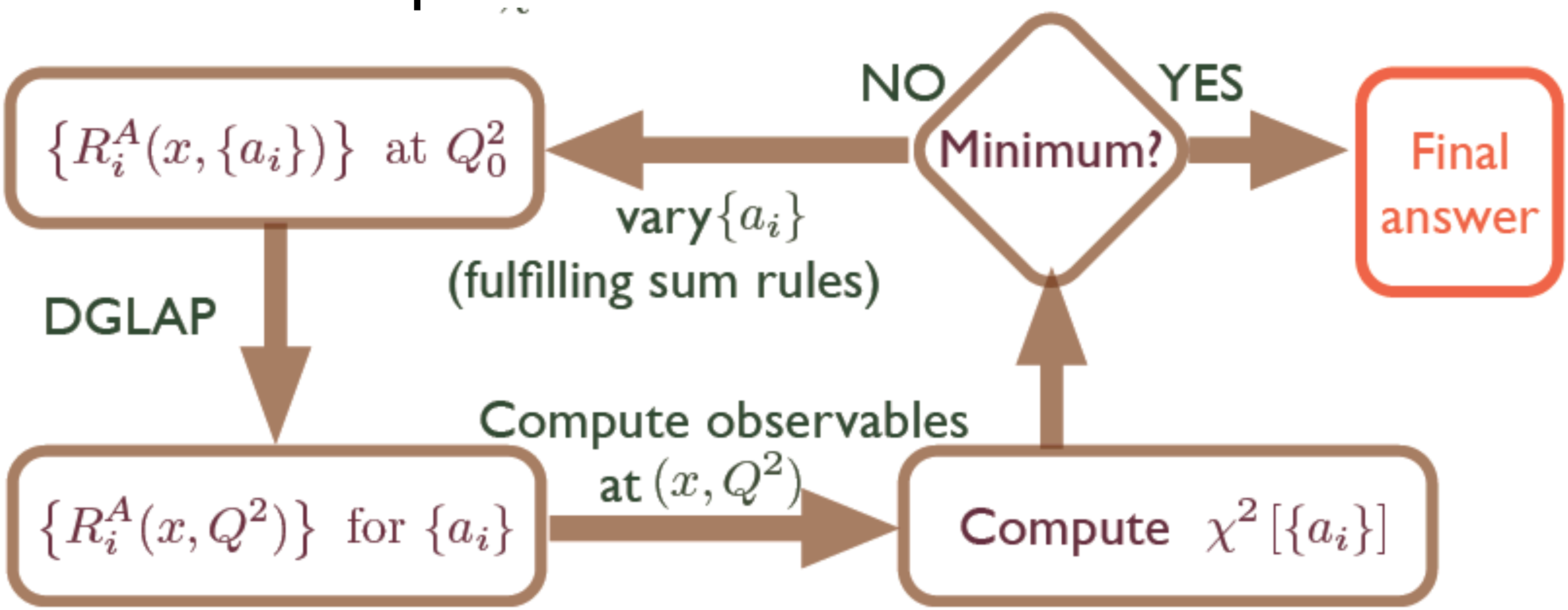
→ All experimental data where you rely on collinear factorization.

→ Several groups: MSTW, CTEQ, NNPDF, ZEUS, H1, Alekhin.

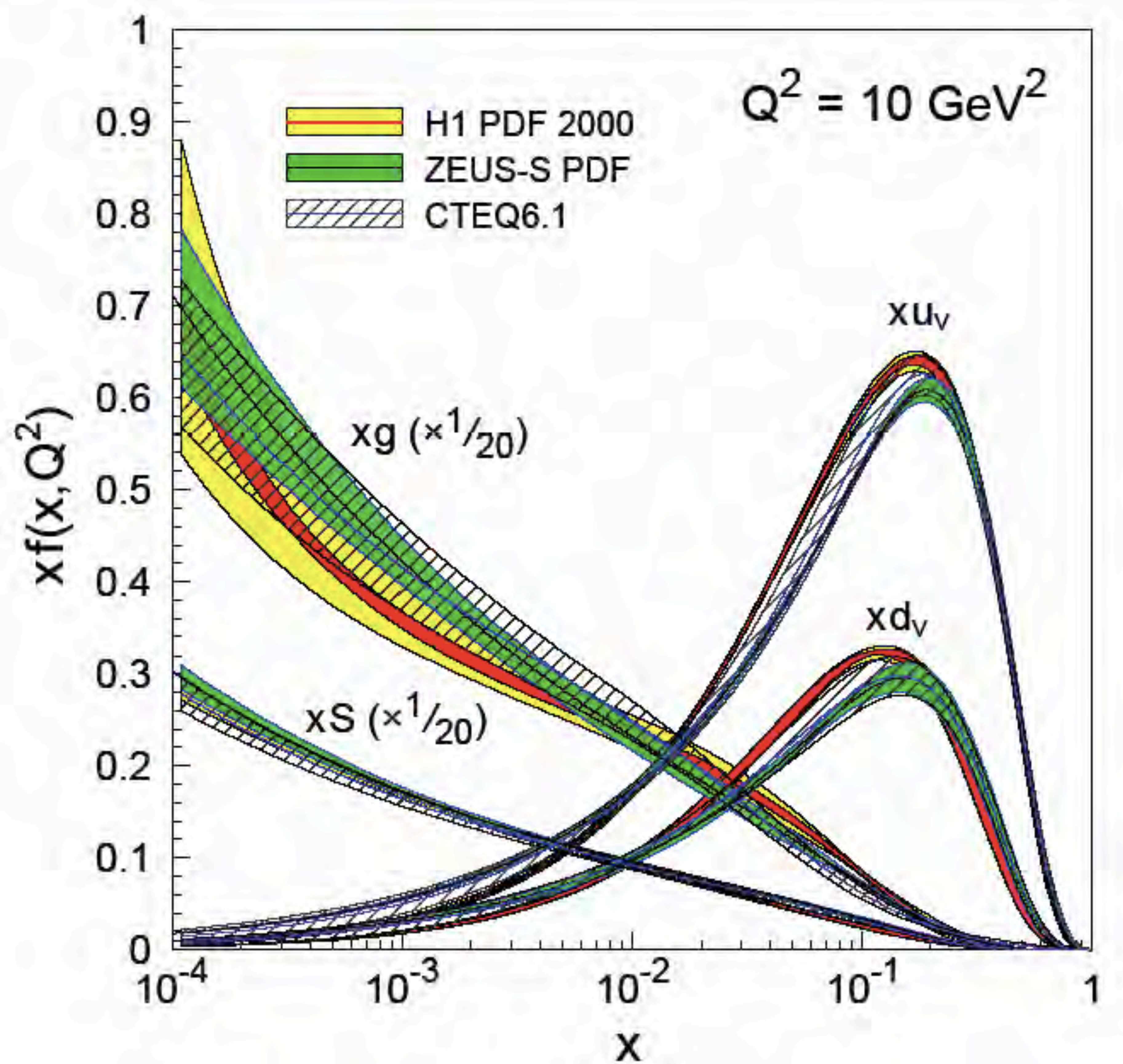
→ Error analysis using variants of the Hessian method.

→ Analysis at LO, NLO and even NNLO (MSTW).

→ Initial conditions for several pdf's: CTEQ, MSTW [$f_i(x,Q_0^2)=A_i x^{b_i}(1-x)^{c_i}$],... As many restrictions as possible (e.g. ubar=,≠dbar): around 40 parameters in MSTW and CTEQ (ZEUS, H1 smaller number). NNPDF: around 400 parameters.

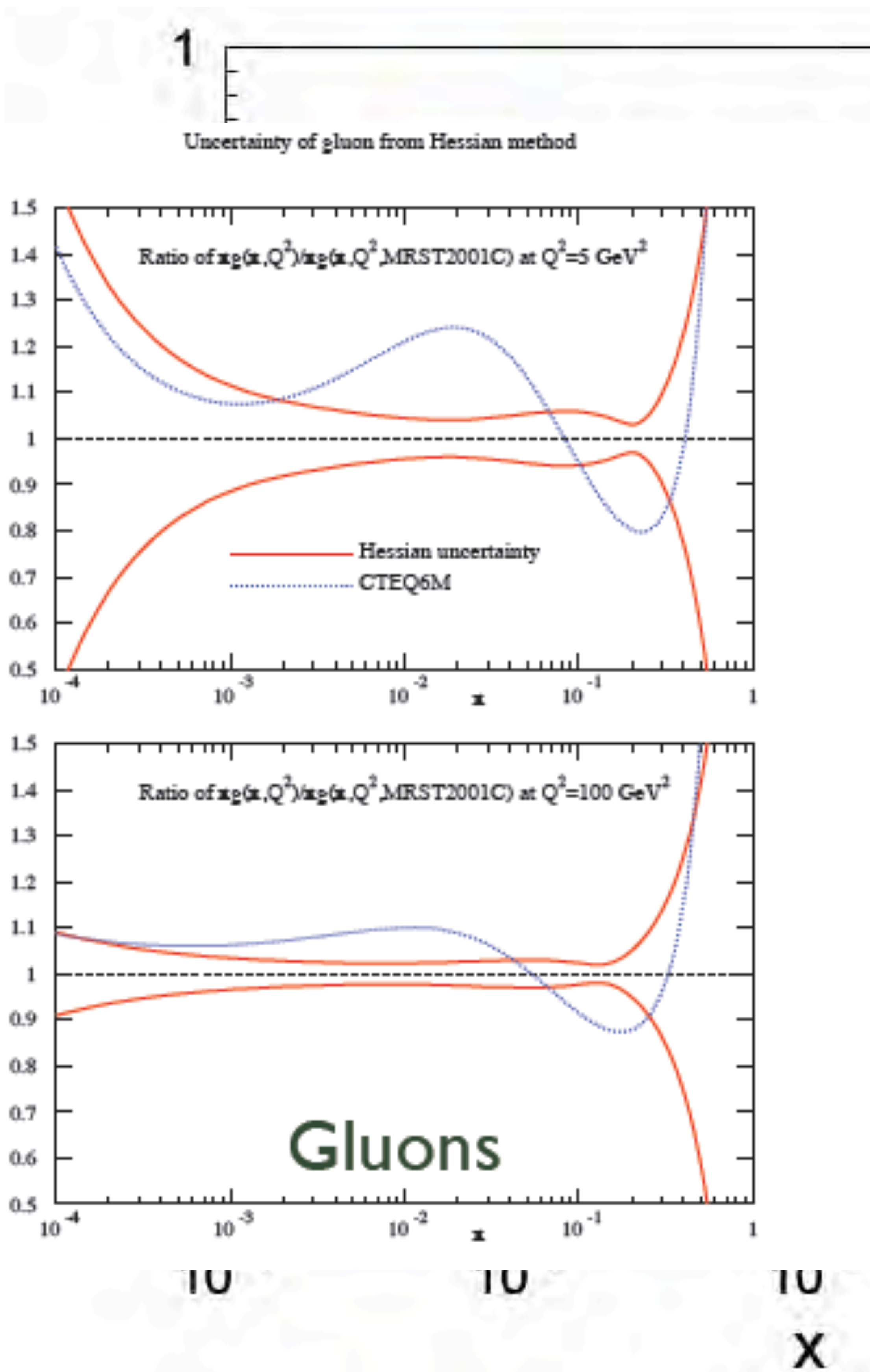


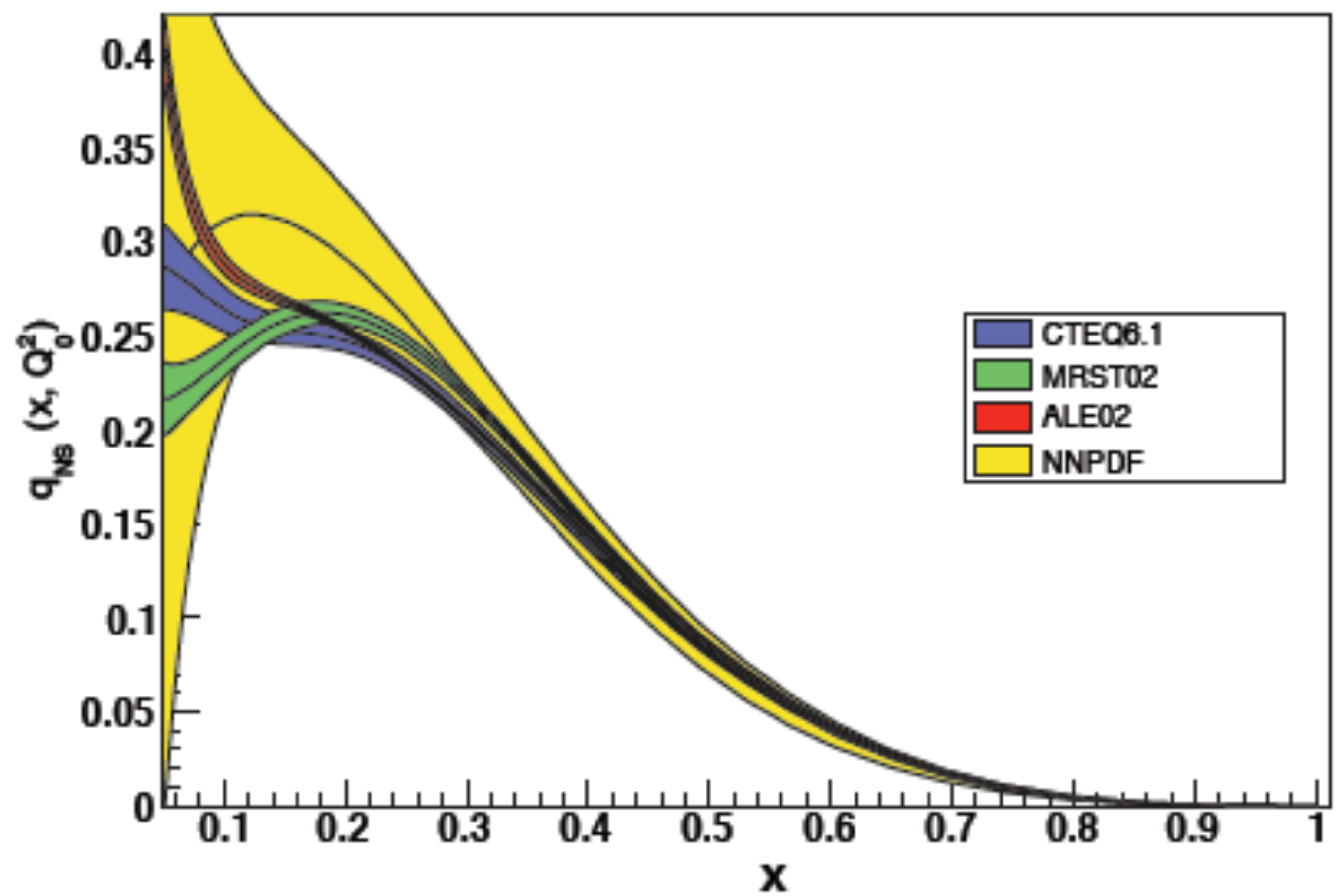
Global fits:



Sea decomposition at small x difficult.

Global fits:





Non-singlet

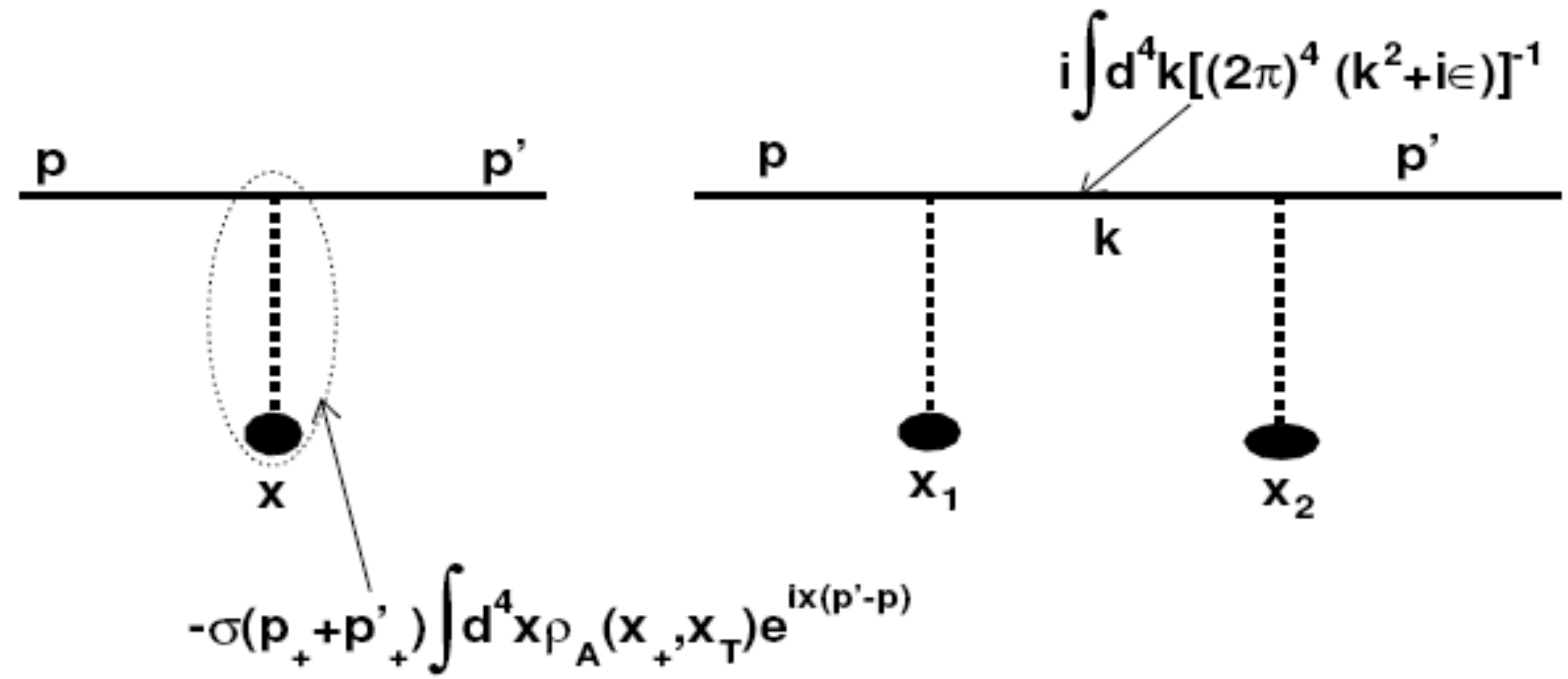
Two scattering case (P1):

$$\mathrm{i}t\,(q=0)=\mathrm{i}t_{\mathrm{forw}}=-\sigma$$

$$\mathrm{i}\mathcal{T}_n(q=0)=-\sigma_A^n$$

$$q=p'-p$$

$$T_A(x_T)=\int_{-\infty}^{+\infty}\mathrm{d}x_+\,\rho_A(x_+,x_T)$$



$$c(p_+,p'_+)\mathrm{i}\mathcal{T}_1(q)=\ \mathrm{i}t_{\mathrm{forw}}c(p_+,p'_+)A\int\mathrm{d}^2x_T\,T_A(x_T)\,\mathrm{e}^{-\mathrm{i}x_T\cdot(p'_T-p_T)}\quad\Rightarrow\quad\sigma_A^1=A\sigma$$

$$\begin{aligned}c(p_+,p'_+)\mathrm{i}\mathcal{T}_2(q)=&\ c(p_+,p'_+)A(A-1)(\mathrm{i}t_{\mathrm{forw}})^2\\&\times\int\frac{\mathrm{d}^2k_T}{(2\pi)^2}\,\mathrm{d}x_{1+}\,\mathrm{d}x_{2+}\,\mathrm{d}^2x_{1T}\,\mathrm{d}^2x_{2T}\,\exp\left(-\mathrm{i}k_T^2(x_{2+}-x_{1+})/(2p_+)\right)\\&\times\exp(-\mathrm{i}[x_{1T}\cdot(k_T-p_T)+x_{2T}\cdot(p'_T-k_T)]\rho_A(x_{1+},x_{1T})\\&\times\rho_A(x_{2+},x_{2T})\theta(x_{2+}-x_{1+}),\ )\end{aligned}$$

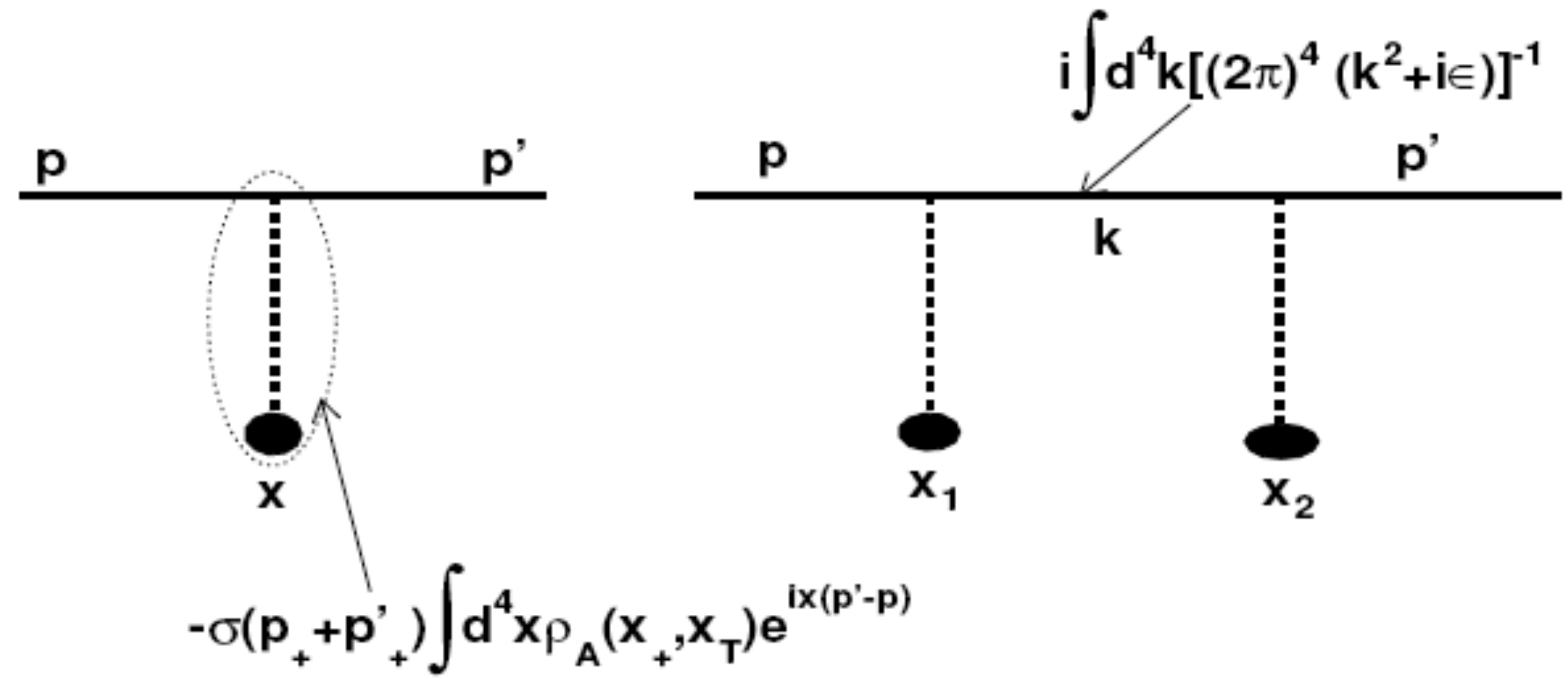
Two scattering case (P1):

$$i t\,(q=0) = i t_{\rm forw} = -\sigma$$

$$i\mathcal{T}_n(q=0) = -\sigma_A^n$$

$$q = p' - p$$

$$T_A(x_T) = \int_{-\infty}^{+\infty} dx_+\, \rho_A(x_+, x_T)$$



$$c(p_+, p'_+) i\mathcal{T}_1(q) = \; i t_{\rm forw} c(p_+, p'_+) A \int d^2x_T\, T_A(x_T)\, e^{-ix_T\cdot(p'_T - p_T)} \Rightarrow \quad \sigma_A^1 = A\sigma$$

$$\begin{aligned} c(p_+, p'_+) i\mathcal{T}_2(q) = {}& c(p_+, p'_+) A(A-1)(i t_{\rm forw})^2 \\ & \times \int \frac{d^2k_T}{(2\pi)^2}\, dx_{1+}\, dx_{2+}\, d^2x_{1T}\, d^2x_{2T} \exp\left(-ik_T^2(x_{2+} - x_{1+})/(2p_+)\right) \\ & \times \exp(-i[x_{1T}\cdot(k_T - p_T) + x_{2T}\cdot(p'_T - k_T)]\rho_A(x_{1+}, x_{1T}) \\ & \times \rho_A(x_{2+}, x_{2T})\theta(x_{2+} - x_{1+}), \,) \end{aligned}$$

Coherence length, shadowing (P1):

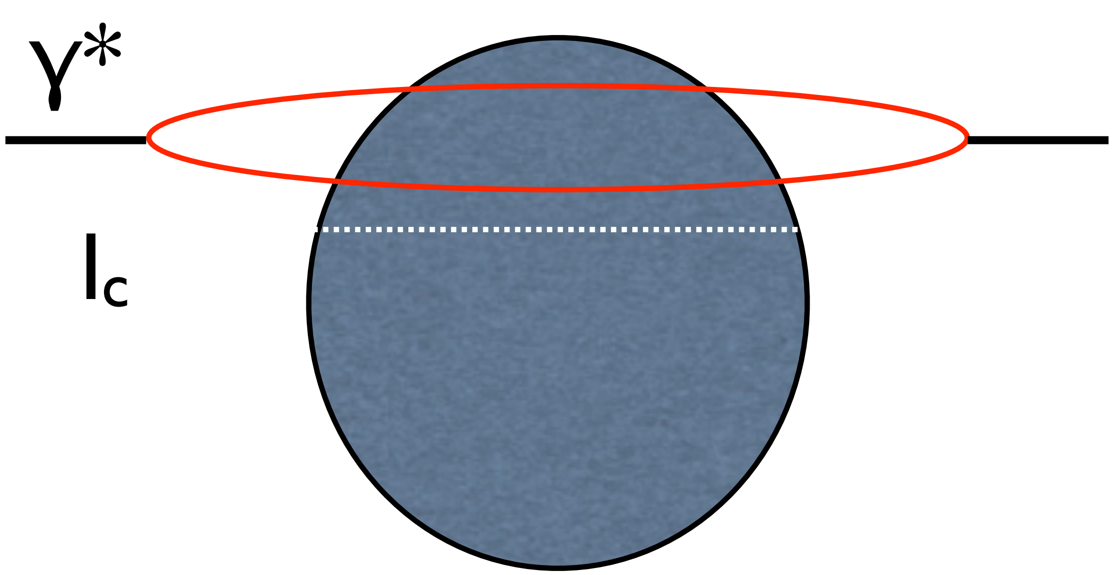
$$\exp\left[-\mathrm{i}k_T^2(x_{2+}-x_{1+})/(2p_+)\right] = \exp\left[-\mathrm{i}(x_{2+}-x_{1+})/l_c\right], \text{ with } l_c = 2p_+/k_T^2$$

A) $p_+ \to 0 \qquad \mathrm{i}\mathcal{T}_2(q) \to 0$

B) $p_+ \to \infty, \exp\left[-\mathrm{i}(x_{2+}-x_{1+})/l_c\right] \to 1$

$$\mathrm{i}\mathcal{T}_2(q) = \frac{A(A-1)}{2}(\mathrm{i}t_{\mathrm{forw}})^2 \int \mathrm{d}^2x_T\, \mathrm{e}^{-\mathrm{i}x_T\cdot(p'_T-p_T)} T_A^2(x_T),$$

$$\sigma_A^2 = -\frac{A(A-1)}{2}\int \mathrm{d}^2x_T [T_A(x_T)\sigma]^2$$



The lifetime of the qqbar fluctuation is $\geq R_A$ for $x \leq 0.1A^{-1/3}$.

$$\tau \sim \frac{1}{Q} \times \frac{E_{\mathrm{lab}}}{Q} \simeq \frac{W^2}{2m_{\mathrm{nucleon}}Q^2} \simeq \frac{1}{2m_{\mathrm{nucleon}}x}$$

Global fits:

$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j \qquad H_{ij} \equiv \frac{1}{2} \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}\Big|_{a=a^0} \qquad \chi^2 \approx \chi_0^2 + \sum_i z_i^2$$

$$S_0 = (0, 0, 0, \ldots, 0)$$

$$\Delta\chi^2 \equiv \sum_i \frac{\Delta\chi^2(z_i^+) + \Delta\chi^2(z_i^-)}{2N} \approx \sum_i \frac{(z_i^+)^2 + (z_i^-)^2}{2N} \qquad S_1^{\pm} = \pm\delta z_1^{\pm}\,(1, 0, 0, \ldots, 0)$$

$$S_2^{\pm} = \pm\delta z_2^{\pm}\,(0, 1, 0, \ldots, 0)$$

$$\vdots$$

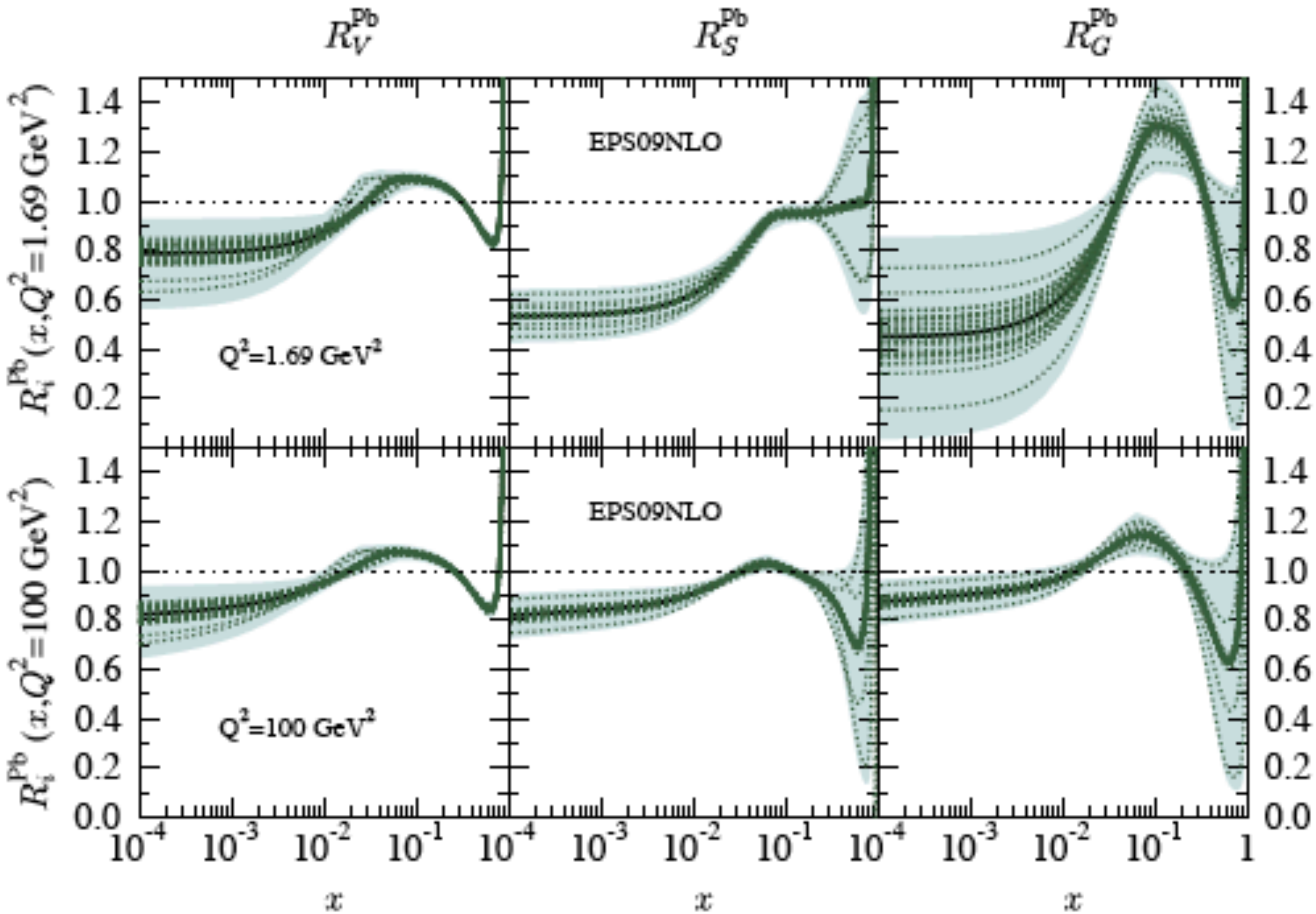
$$(\Delta X^+)^2 \approx \sum_k \left[\max\left\{X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0\right\}\right]^2$$

$$(\Delta X)^2_{\rm extremum} \approx \Delta\chi^2 \sum_j \left(\frac{\partial X}{\partial z_j}\right)^2$$

$$(\Delta X^-)^2 \approx \sum_k \left[\max\left\{X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0\right\}\right]^2$$

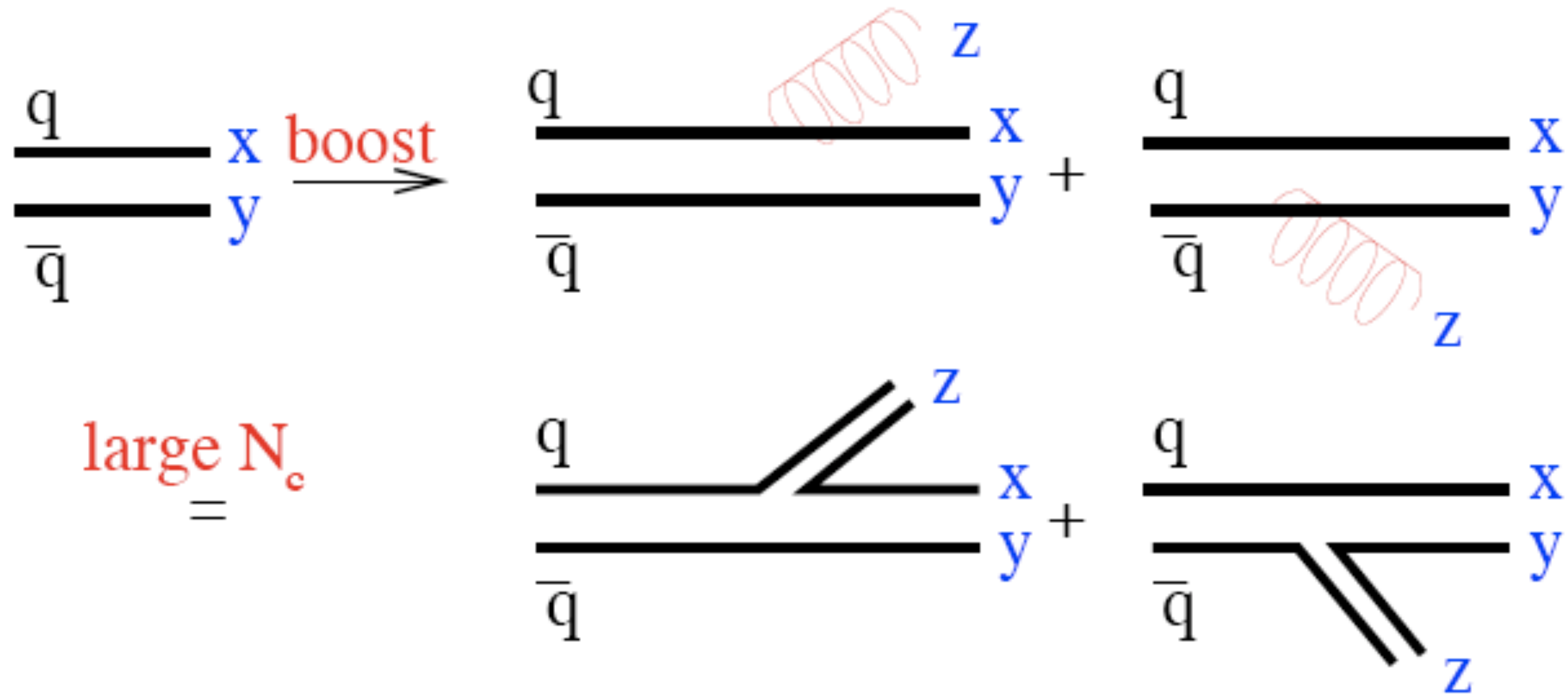
Note: any error analysis is linked to a functional form for the i.c. (NNPDF implies more flexibility); pdf's errors to be used, too.

Global fits:



Note: any error analysis is linked to a functional form for the i.c. (NNPDF implies more flexibility); pdf's errors to be used, too.

The BK equation:



- Neglecting the difference between <W† W W† W>$_{tar}$ and <W† W>$_{tar}$<W† W>$_{tar}$: **BK equation**.

$$\frac{\partial N(r,Y)}{\partial Y} = \int \frac{d^2 z}{2\pi} K(\vec{r},\vec{r}_1,\vec{r}_2)\left[N(r_1,Y)+N(r_2,Y)-N(r,Y)-N(r_1,Y)N(r_2,Y)\right]$$

$$K(\vec{r},\vec{r}_1,\vec{r}_2) = \bar{\alpha}_s \frac{r^2}{r_1^2 r_2^2} \quad , \quad \bar{\alpha}_s = \frac{\alpha_s N_c}{\pi}$$

$$\phi(Y,k,b) = \int \frac{d^2 r}{2\pi r^2} e^{i\vec{k}\cdot\vec{r}} N(Y,r,b)$$

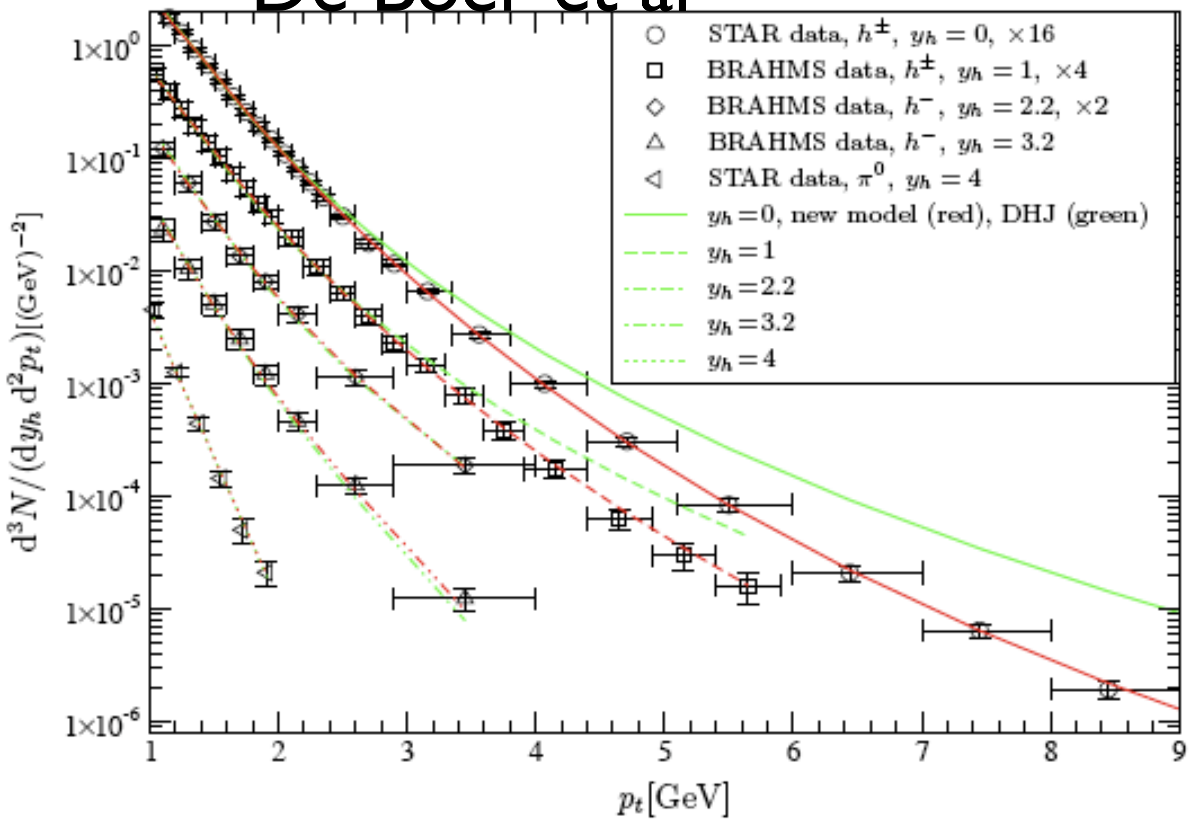
- Neglecting the dependence on impact parameter:

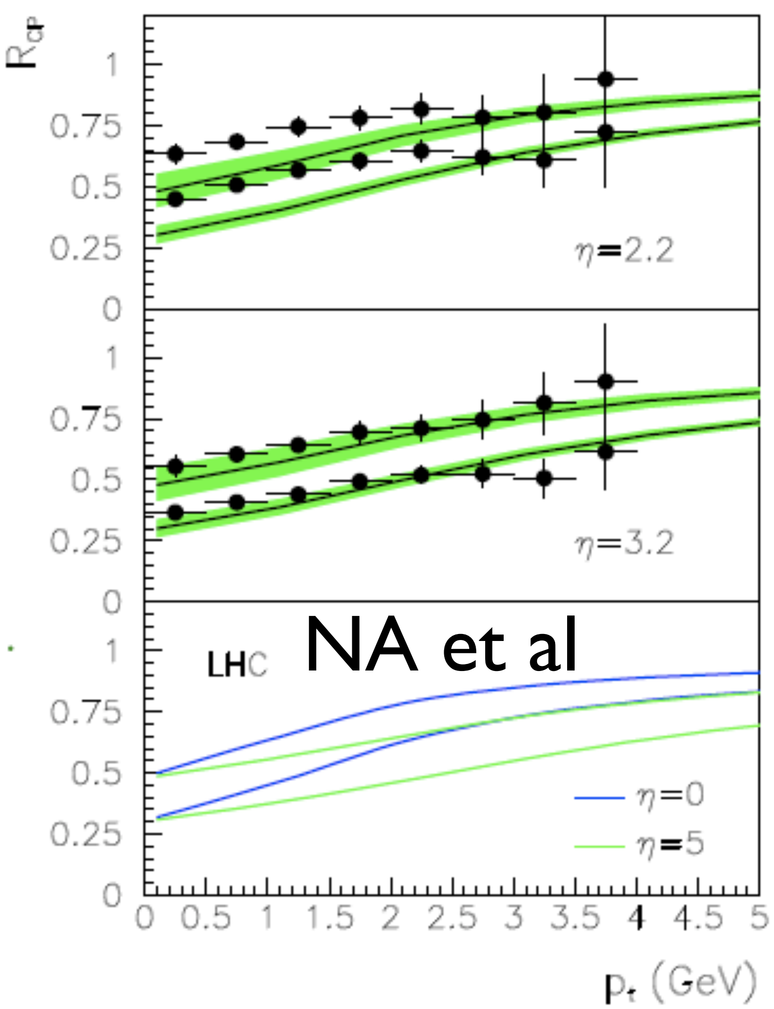
$$\frac{\partial \phi(y,k)}{\partial y} = H_{BFKL} \otimes \phi(y,k) - \phi^2(y,k), \quad y = \bar{\alpha}_s Y$$

pA at RHIC:

- This suppression is compatible with ugd+factorization (dilute-dense): IIM, DHJ, in agreement with ep + $A^{1/3}$ prescription for Q_s^2. It is also compatible with the ratio of geometric ep/eA scaling functions.

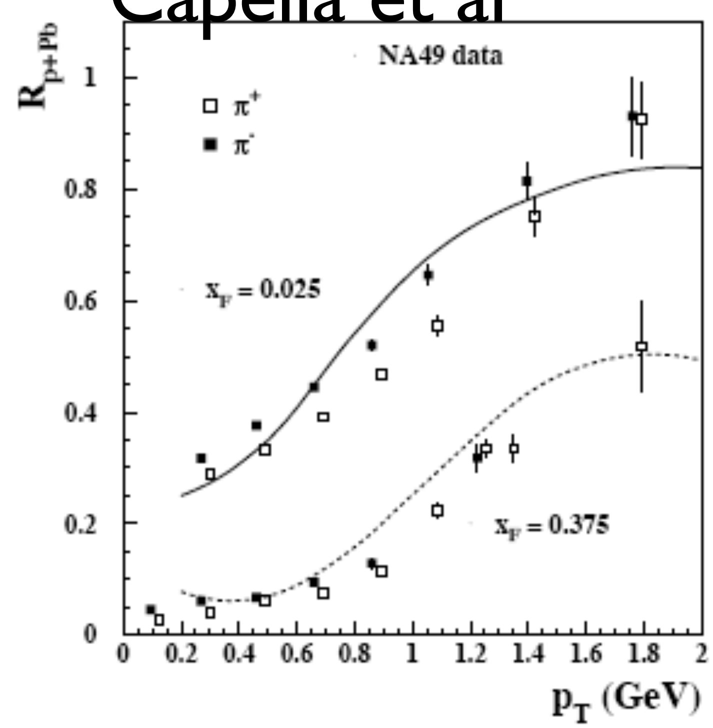
De Boer et al





- Warning: $\langle x_A \rangle > 0.02$, and such suppression also happens at SPS/FNAL energies: finite energy corrections, eloss?

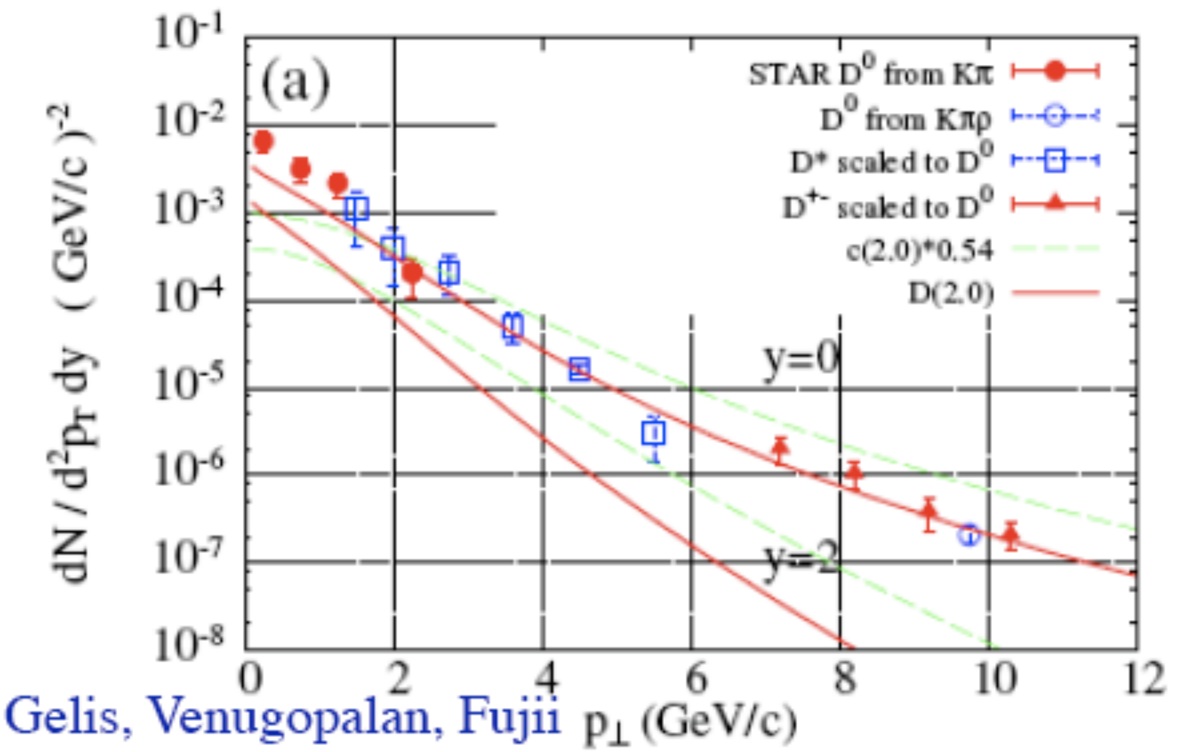
Capella et al

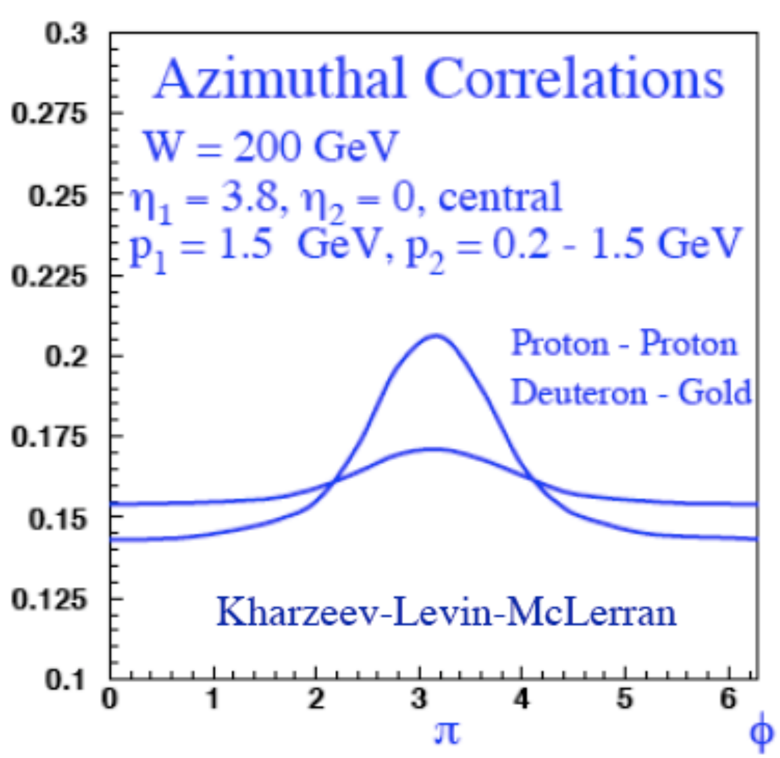


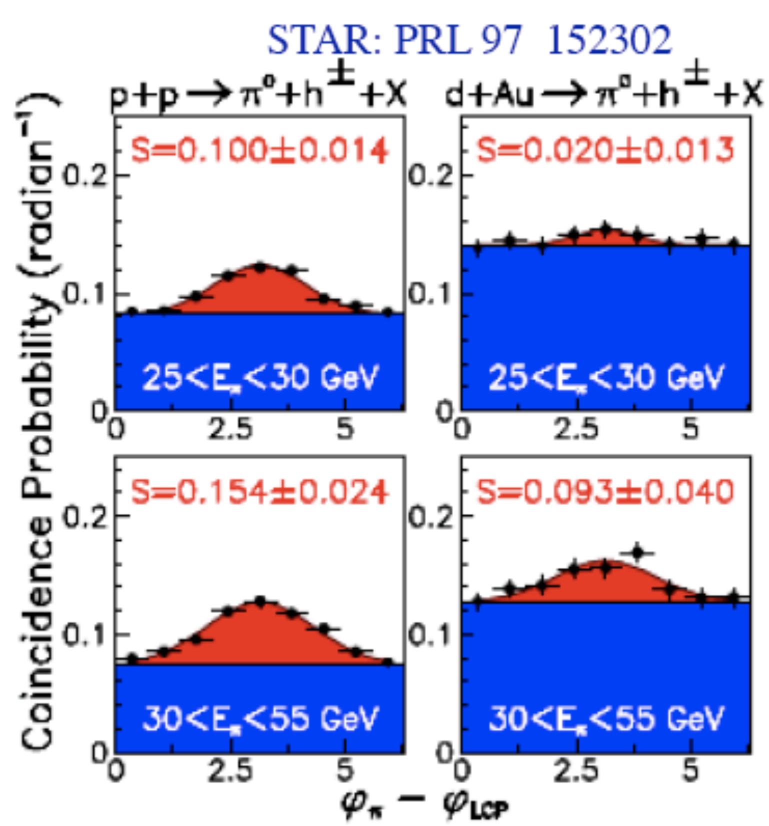
pA at RHIC:

- Azimuthal correlations may also indicate small-x dynamics: tale of the two-particle inclusive distributions (Baier et al, Kovchegov et al, Marquet).

$$\frac{d\sigma}{dy_1\, dy_2\, d^2p_1\, d^2p_2\, d\Delta\phi}$$

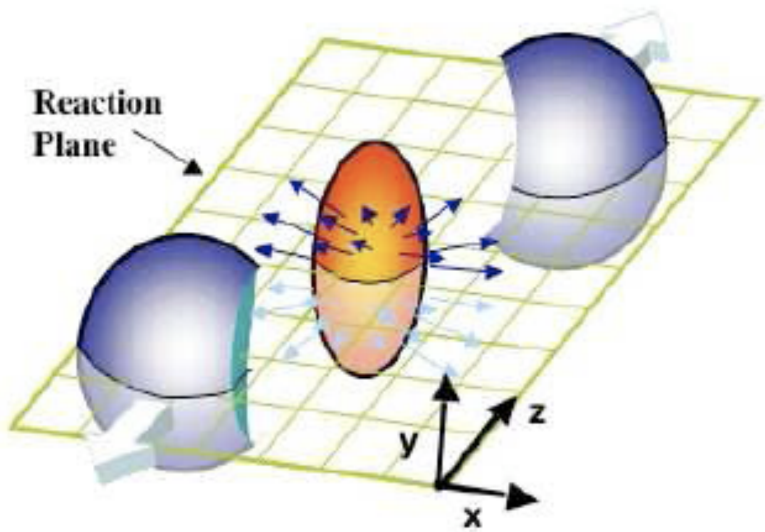


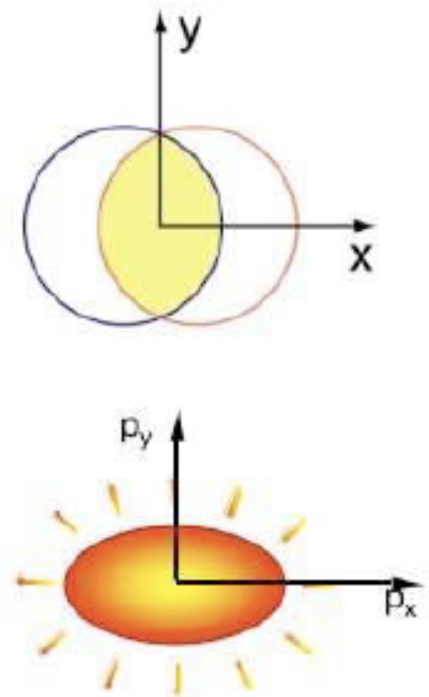


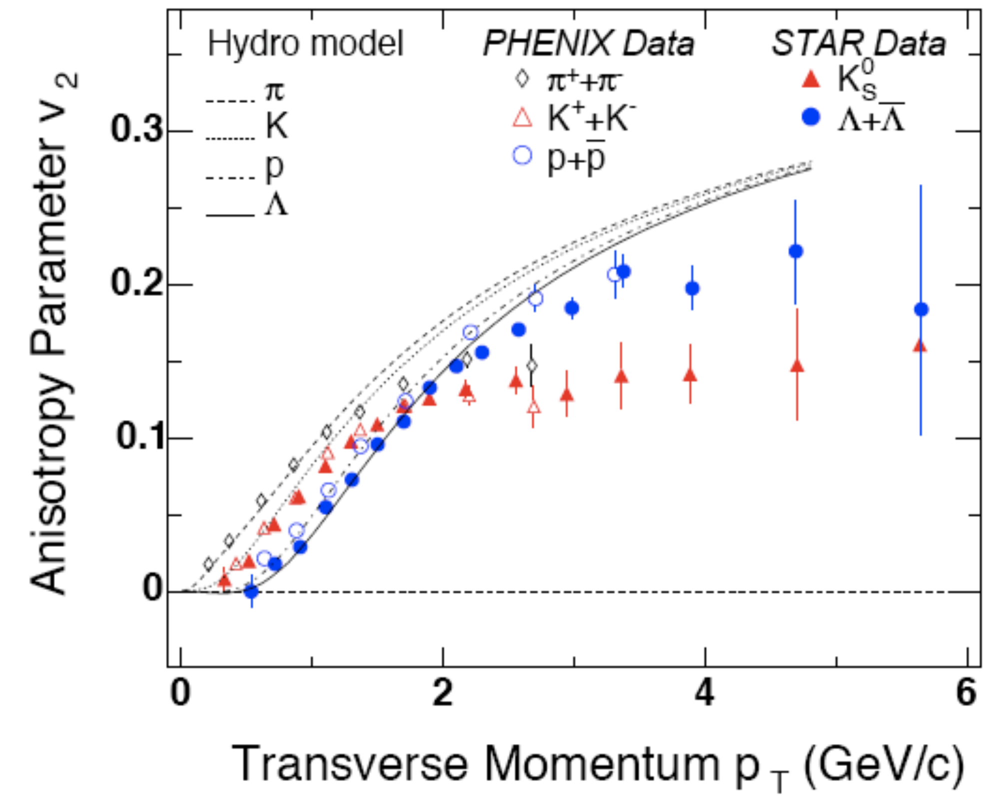


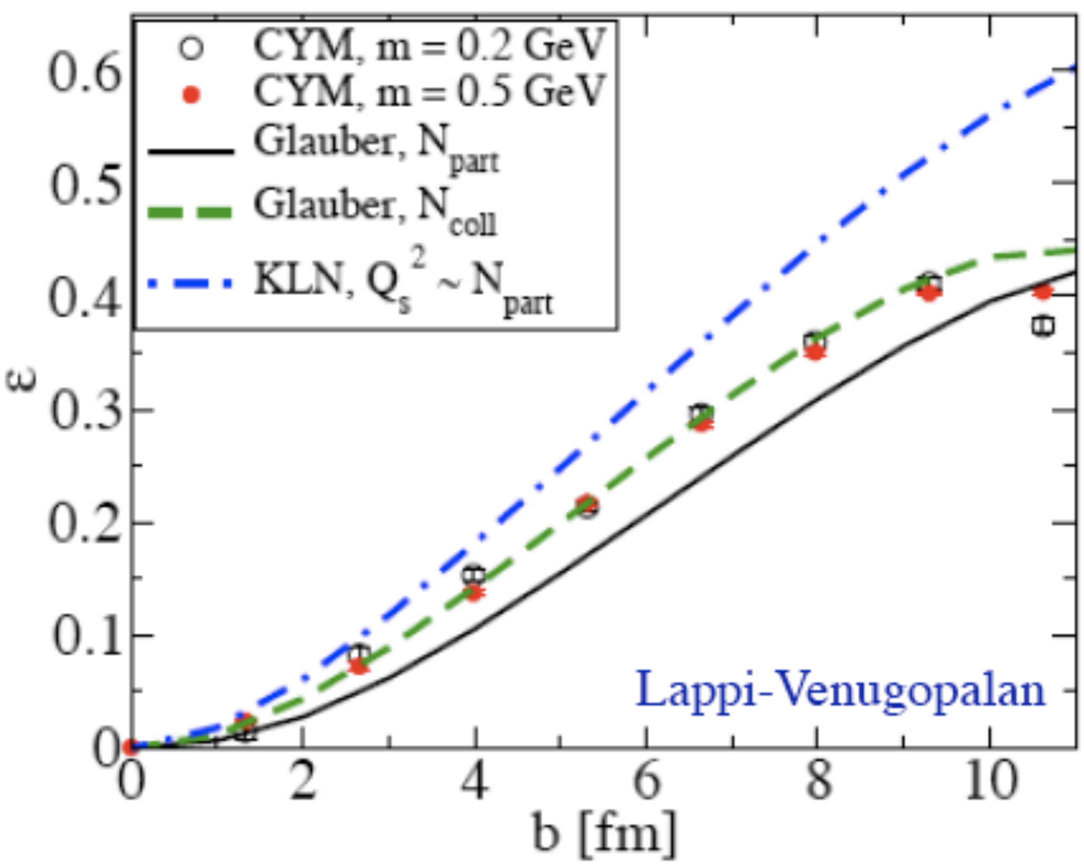
- Charm production described (also Kharzeev et al, Tuchin).

AA at RHIC:









- Initial conditions for hydrodynamical evolution are a key ingredient in those calculations. CGC gives larger eccentricity: room for viscosity or larger equilibration times.
- Uncertainties at the nuclear periphery (NP region).

AA at RHIC:

• CGC may offer initial conditions for QGP formation: transverse fields transform into longitudinal (Glasma) (Lappi et al, Romatschke et al).

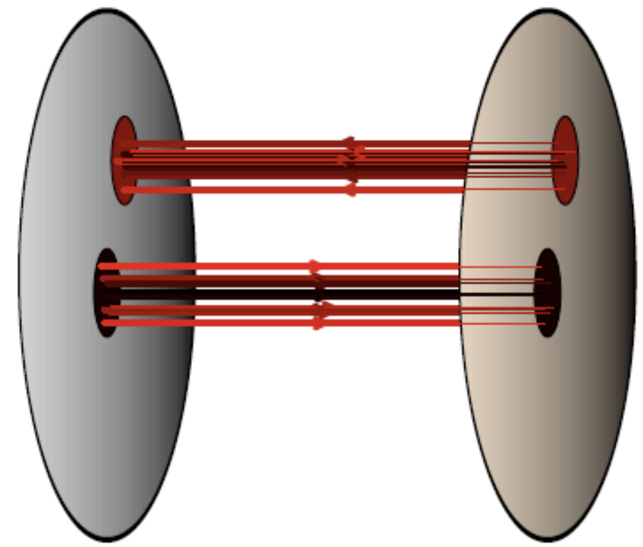
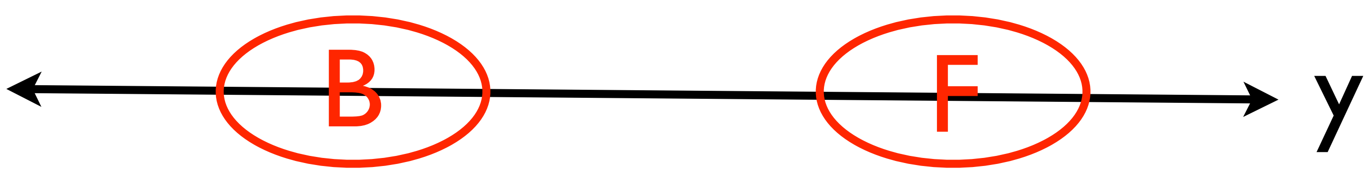


Figure 4: Glasma flux tubes. The transverse size of the flux tubes is of order $1/Q_s$.

• QCD basis for good old string models.

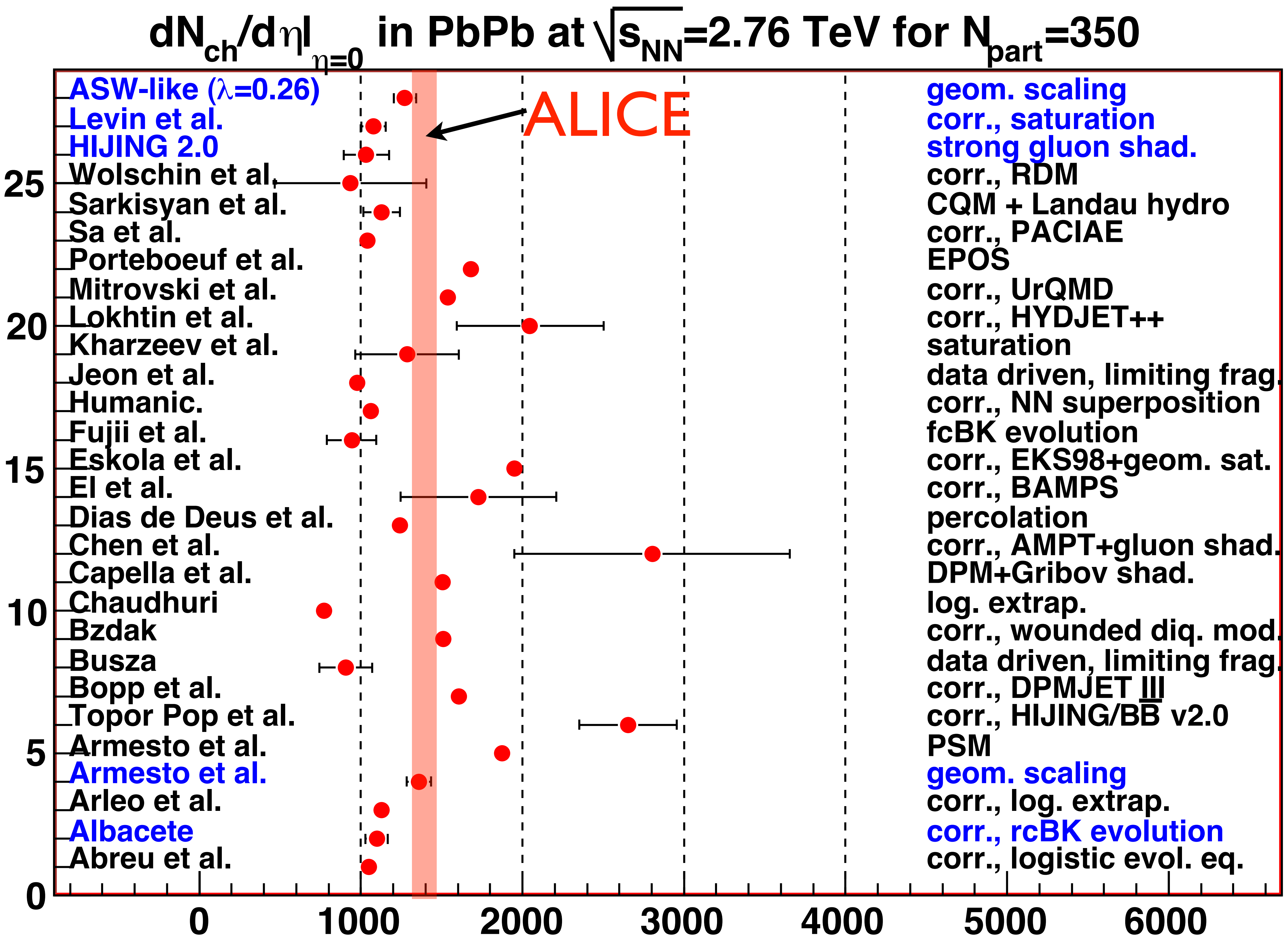


$$\langle n_B \rangle_F = a + b n_F\,, \quad b \equiv D^2_{FB}/D^2_{FF}\,,$$

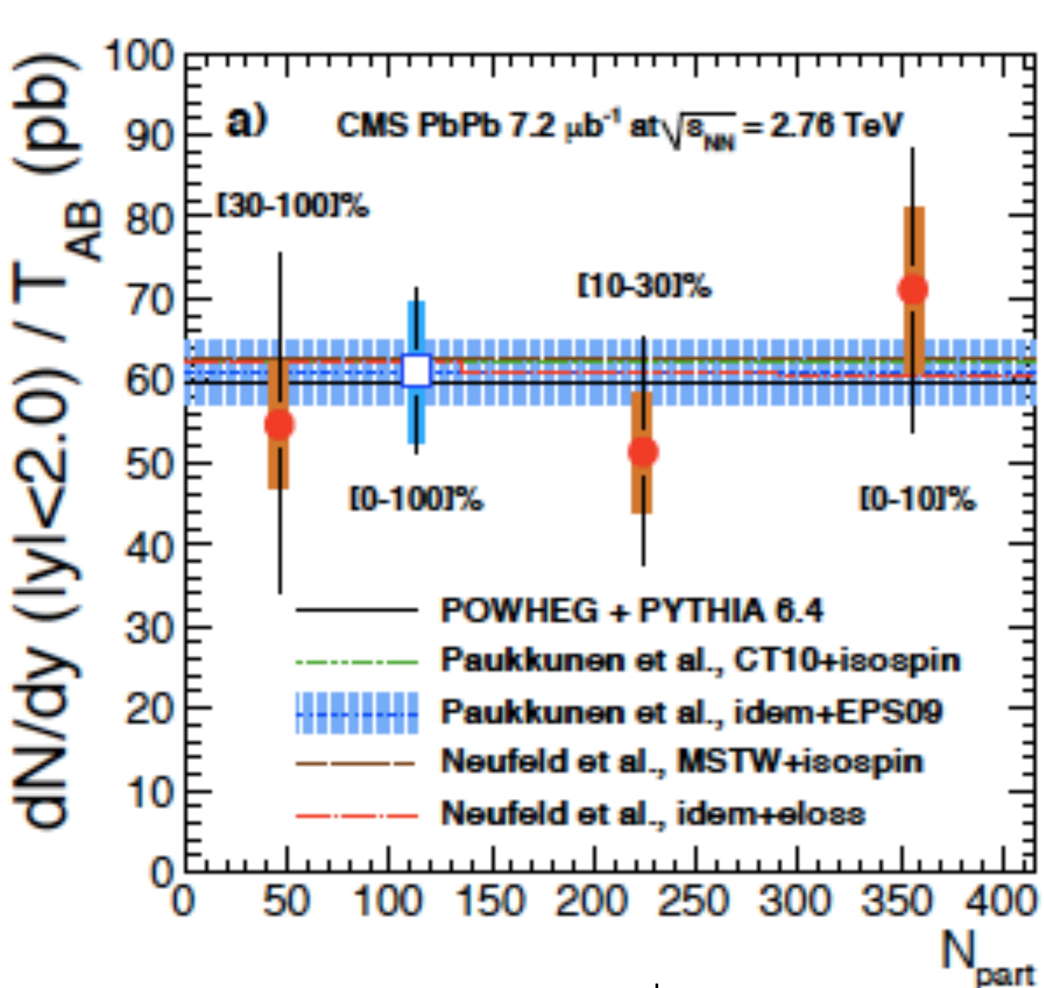
$$b \;=\; \frac{1}{1 + c\alpha_s^2}\,.$$

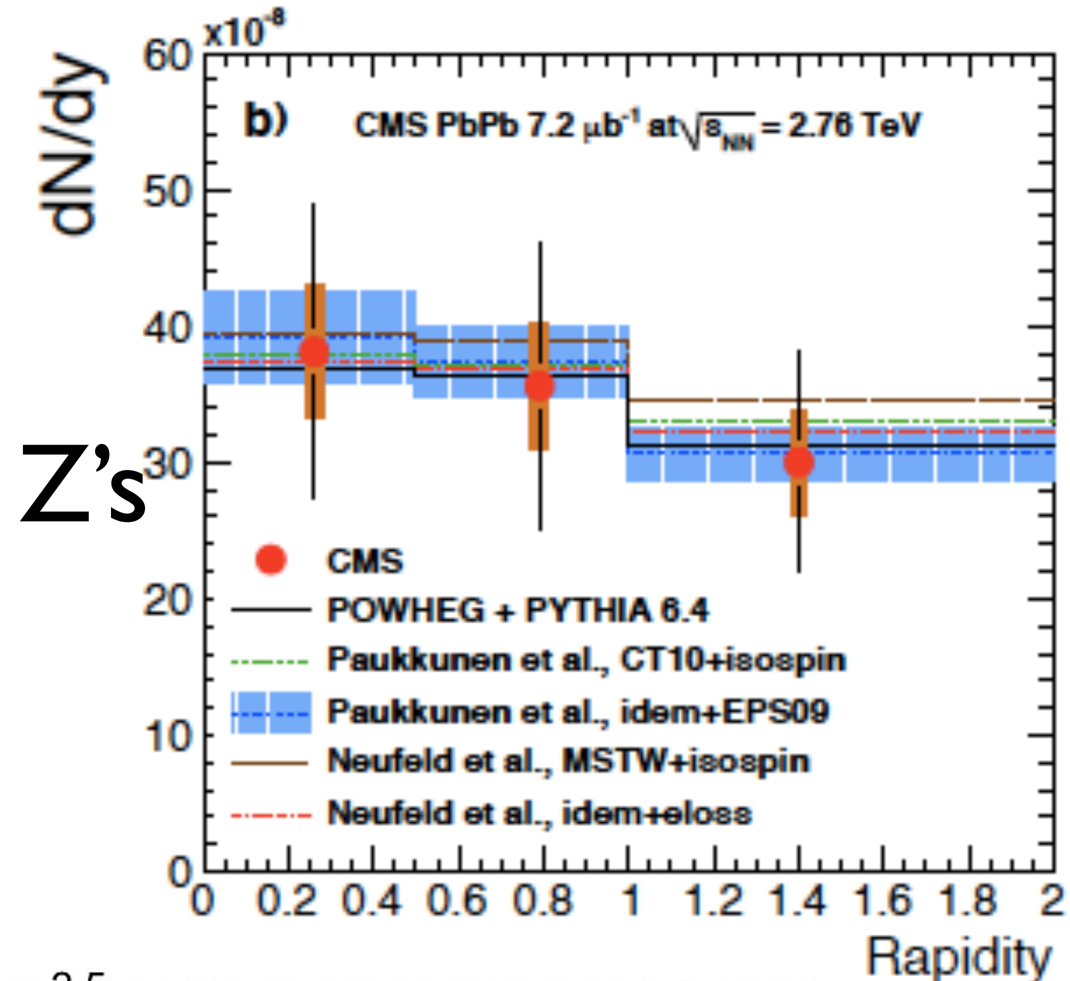
• Correlations in rapidity are a place to look for such origin of particle production (Capella et al, NA et al, Dumitru et al, Fukushima et al).

Multiplicities:

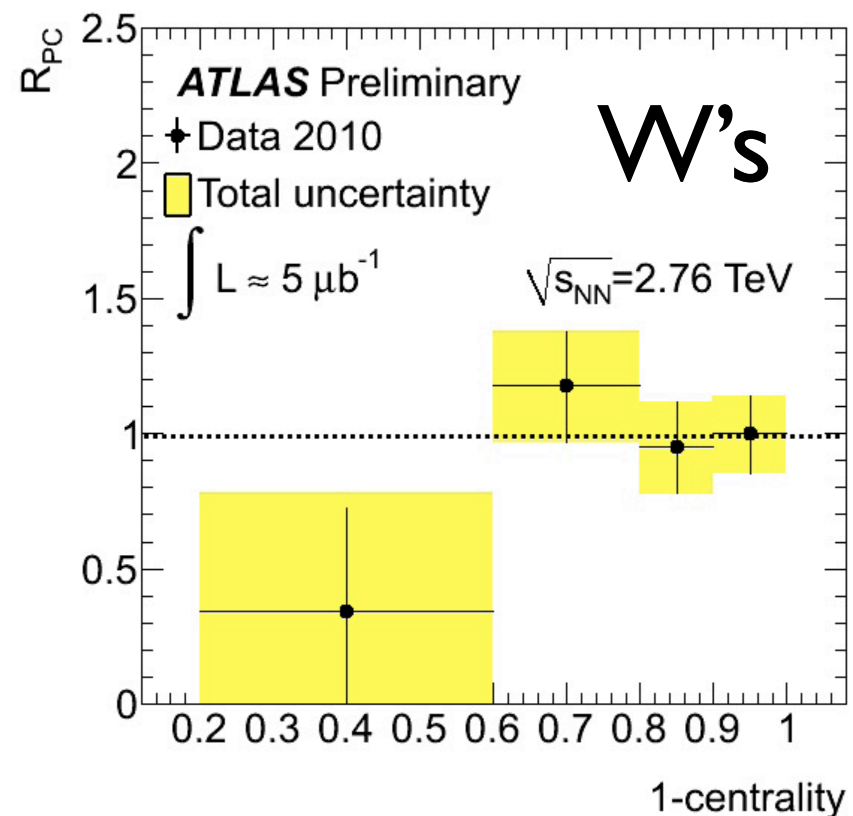


W/Z (LHC-specific):

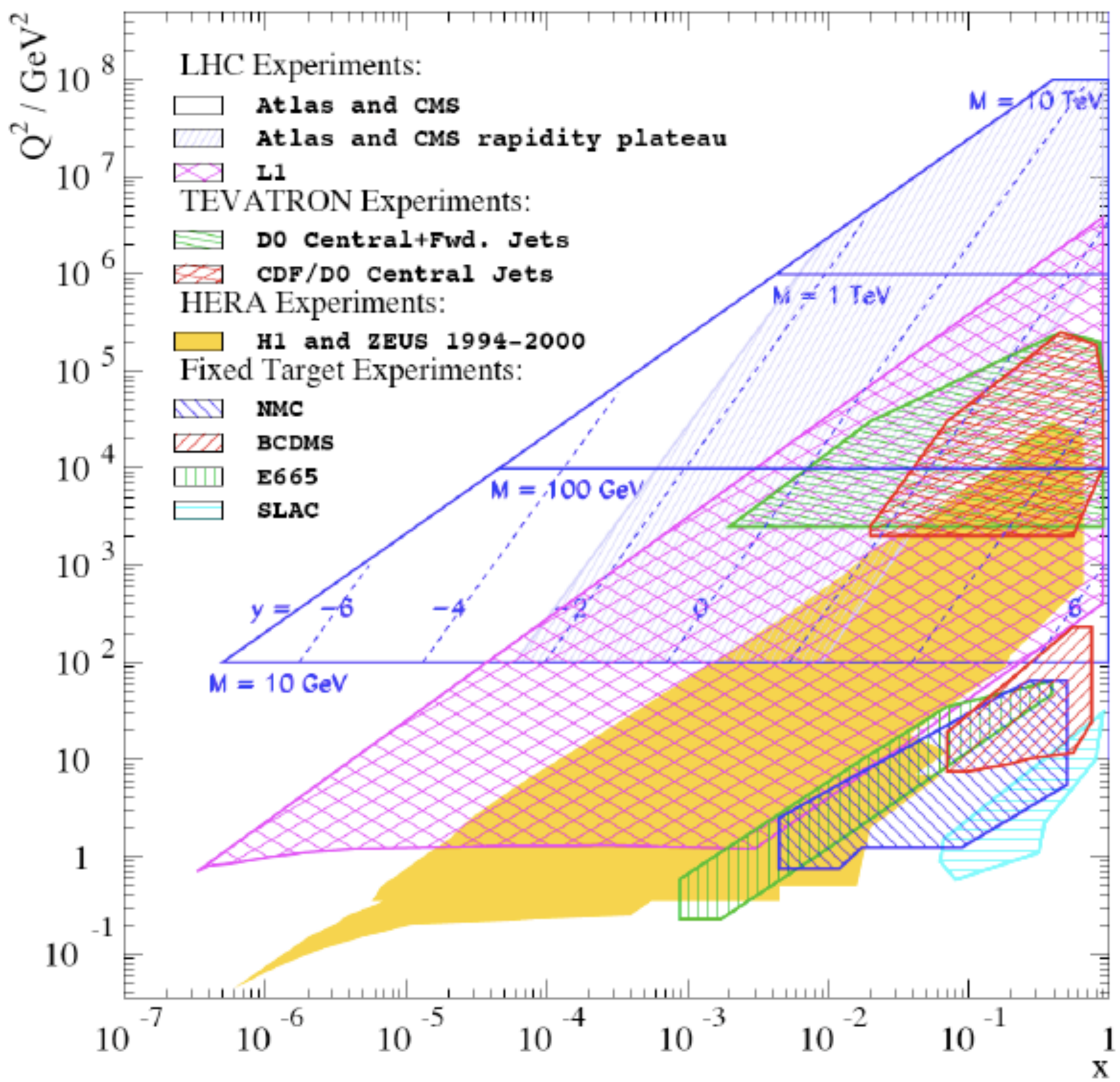


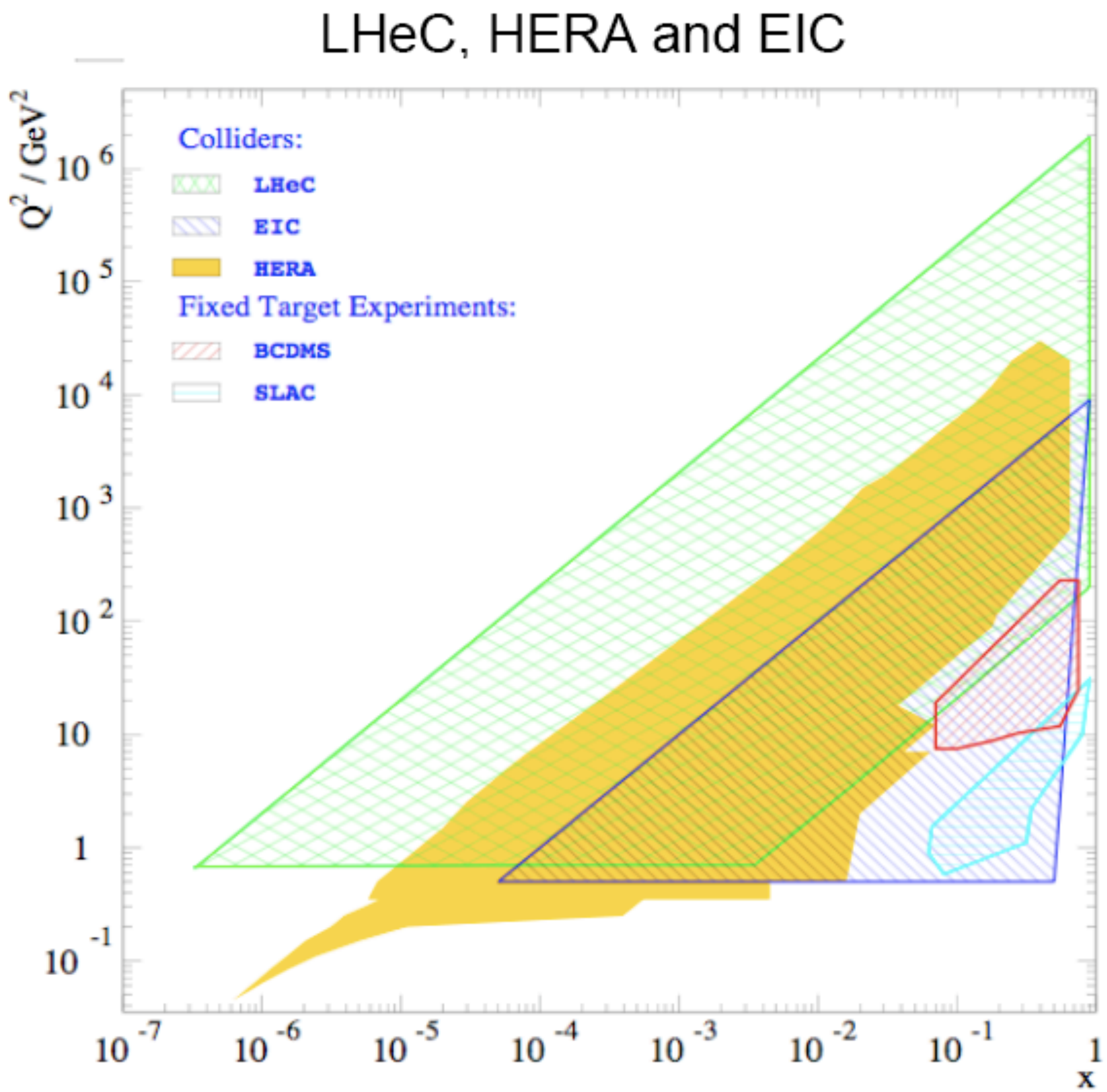


- First Z/W measurement in heavy-ion collisions!!! Benchmark (npdfs) for future.

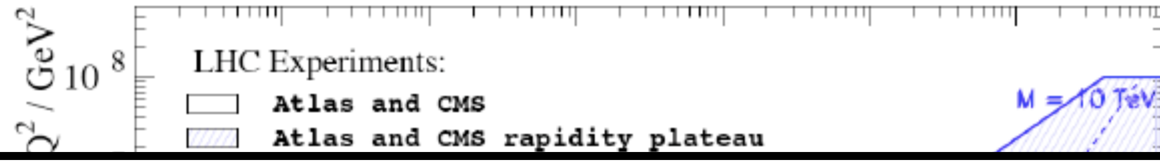


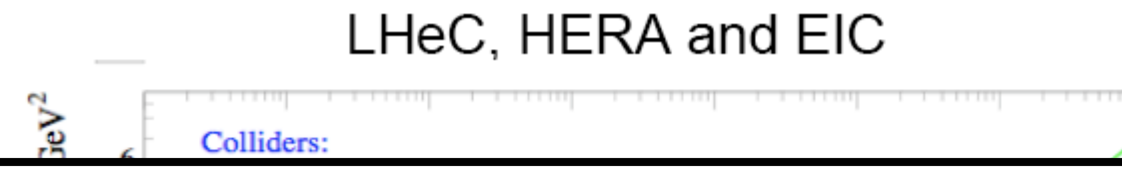
LHC and beyond:



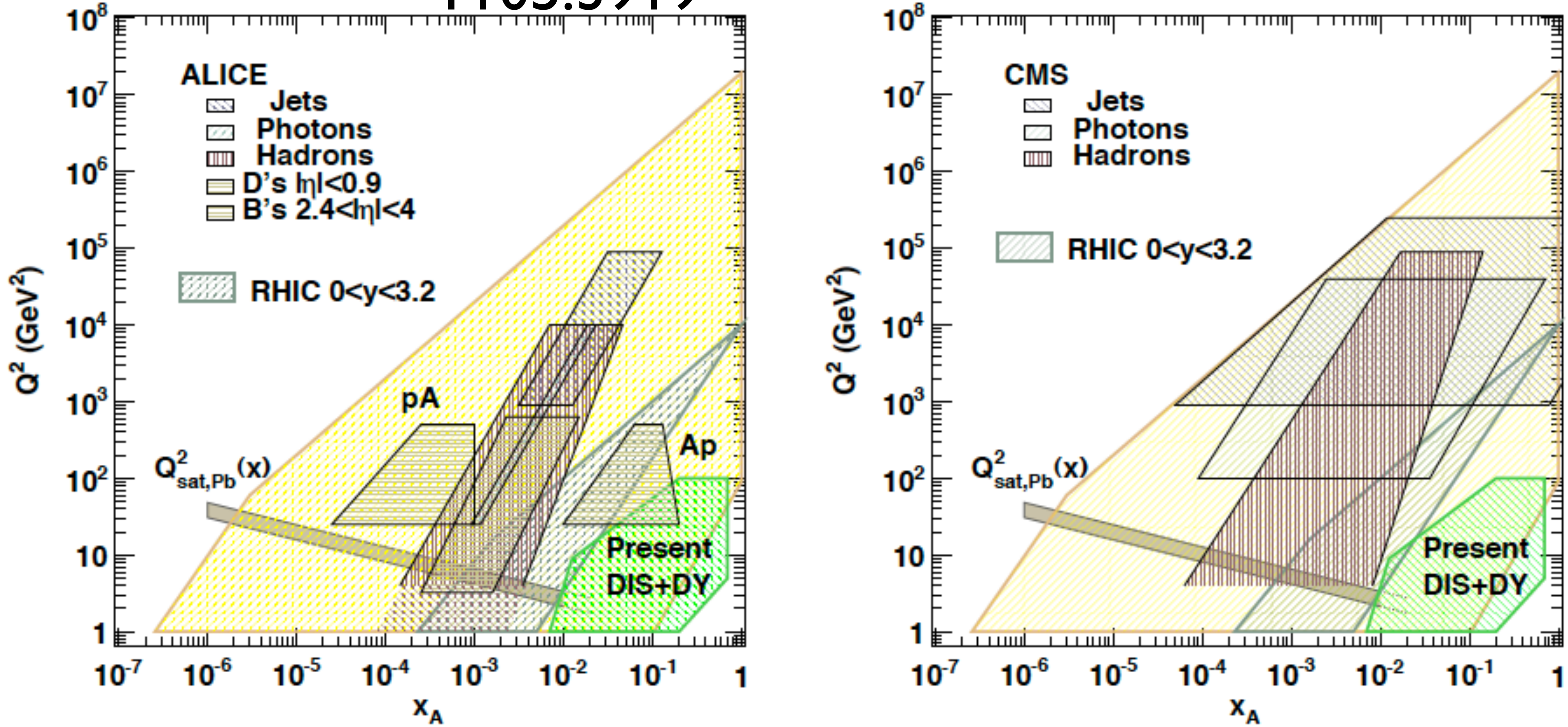


LHC and beyond:





1105.3919



LHC and beyond: