High-p_T probes of excited nuclear medium in the LHC era

Jan Rak

3rd International Conference on New Frontiers in Physics
28 July 2014 to 6 August 2014

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ALICE

HELSINKI INSTITUTE OF PHYSICS

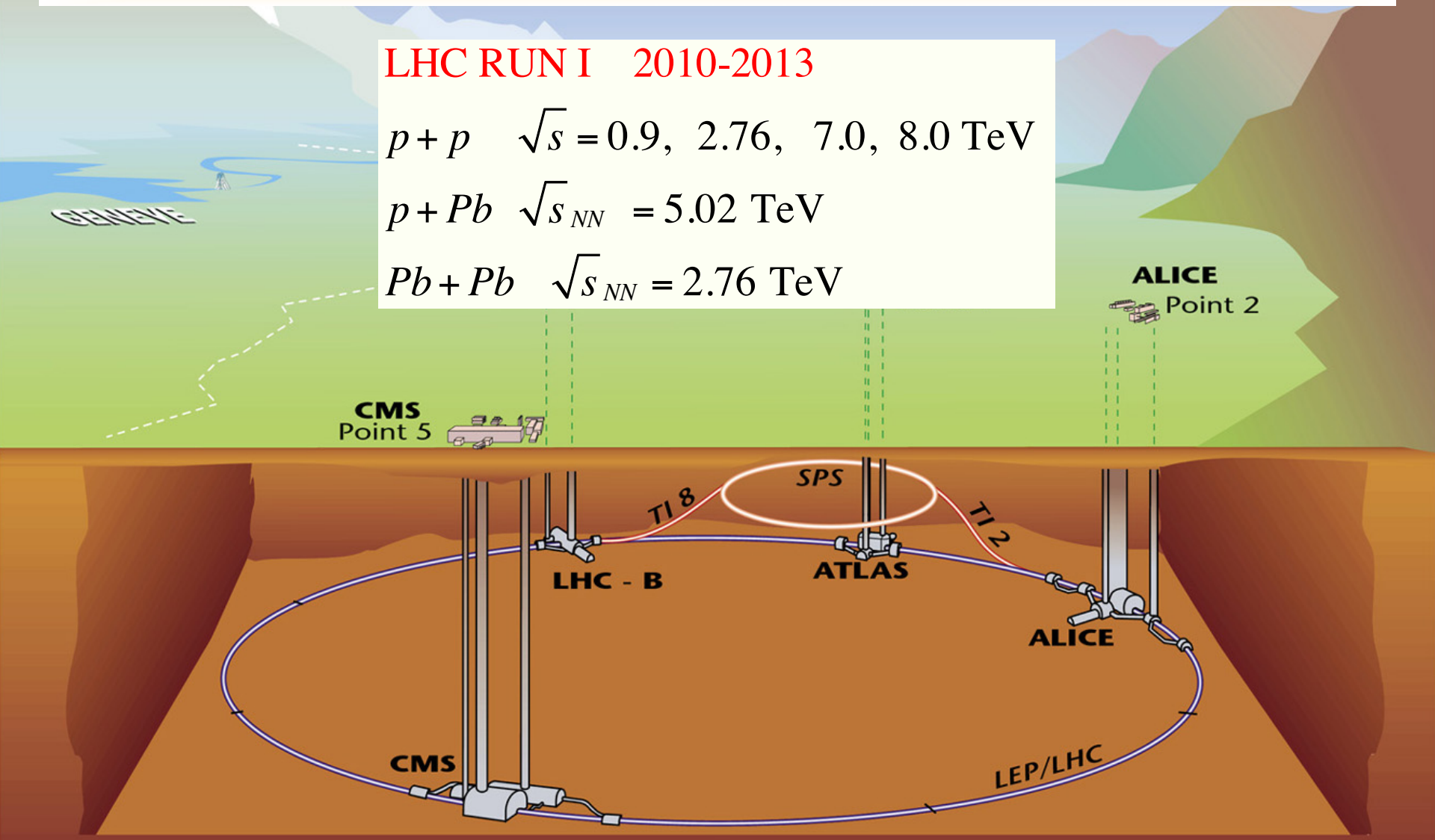
Large Hadron Collider (LHC) CERN

LHC RUN I 2010-2013

$p+p \quad \sqrt{s} = 0.9,\ 2.76,\ 7.0,\ 8.0\ \text{TeV}$

$p+Pb \quad \sqrt{s_{NN}} = 5.02\ \text{TeV}$

$Pb+Pb \quad \sqrt{s_{NN}} = 2.76\ \text{TeV}$



•Circular tunnel 27 km in circumference (old LEP). 25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch

•Design Luminosity: $10^{34}\text{cm}^{-2}\text{s}^{-1}$ ⇒100 fb^{-1}/year, Stored energy/beam: 350 MJ, √s up to 14 TeV

1st Rutherford scattering

High transverse momentum physics always played an important role when probing the structure of matter.

High-p_T actually invented in 1906 by Sir Rutherford. He studied the scattering of α and β radiation on thin sheet of mica [*Phil. Mag*. **12**, 134 (1906)] and observed a rare but violent scattering of α particles.

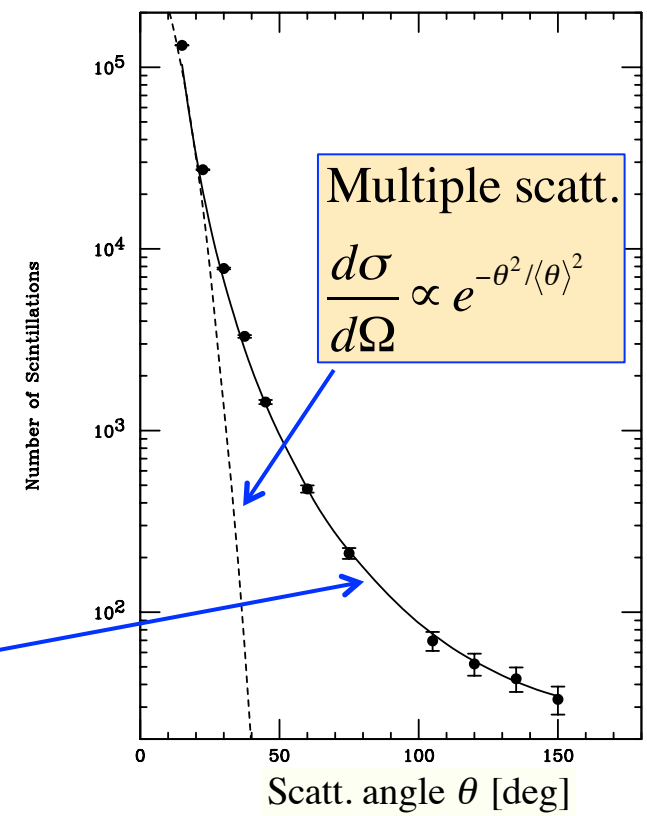
Rutherford remarked about this observation:

"*It was as if one had fired a large naval shell at a piece of tissue paper and it had bounced back*."

➠ Nuclear Physics.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rutherford}} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)}$$

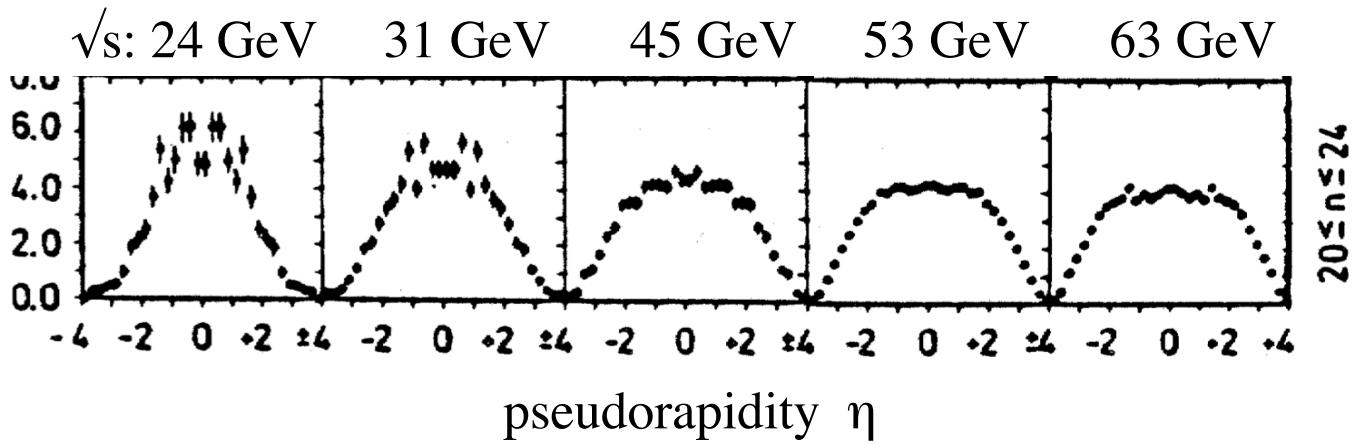
Note power $n = 4$



Limited transverse momentum

1971 CERN Intersecting Storage Rings (ISR) , $\sqrt{s} \sim$ 20-60 GeV

Nucl. Phys. B129, 365 (1977).



Soft particle production - "longitudinal phase space" – dominant effect when increasing $\sqrt{s}$.

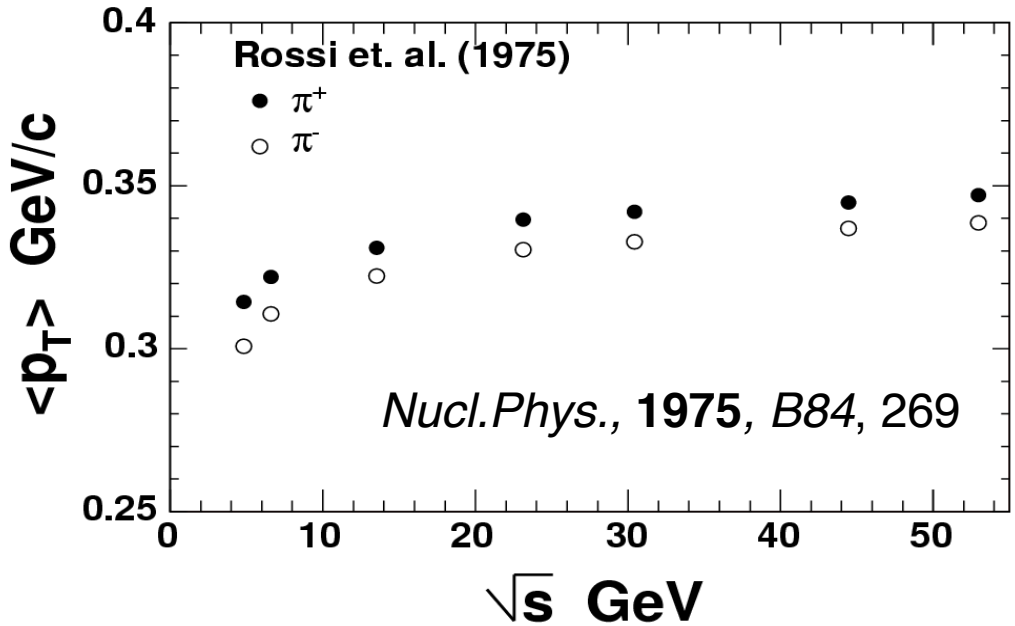
Led G. Cocconi to suggest [*Nucl.Phys.*, **1971**, *B28*, 341-348]:

"*Simple expressions for the fluxes of secondaries produced by protons colliding either with another proton beam (ISR) or with a proton at rest are derived using the general empirical properties of strong interactions.* "

$$\frac{df(p_T)}{dp_T} = \frac{p_T}{b^2} e^{-p_T/b} \quad \text{with } b \sim 1/6 \quad \langle p_T \rangle = 2b \approx 0.33 \text{ GeV/c}$$

Early ISR era

The mean transverse momentum as a function of √s scales.



The independency of $\langle p_T \rangle$ on $\sqrt{s}$ indicates the fundameltal scale

in the problem $\dfrac{\hbar c}{\langle p_T \rangle} \approx 0.6$ fm, proton transverse size $\Rightarrow$

Landau: *Hydrodynamical Model of Particle production*

For an overview see: *Phys.Rev.*, **1973**, *D8*, 859-874

High-p_T in 60ties

J. A. Appel et al., Z. Phys. C 30, 1 (1986)

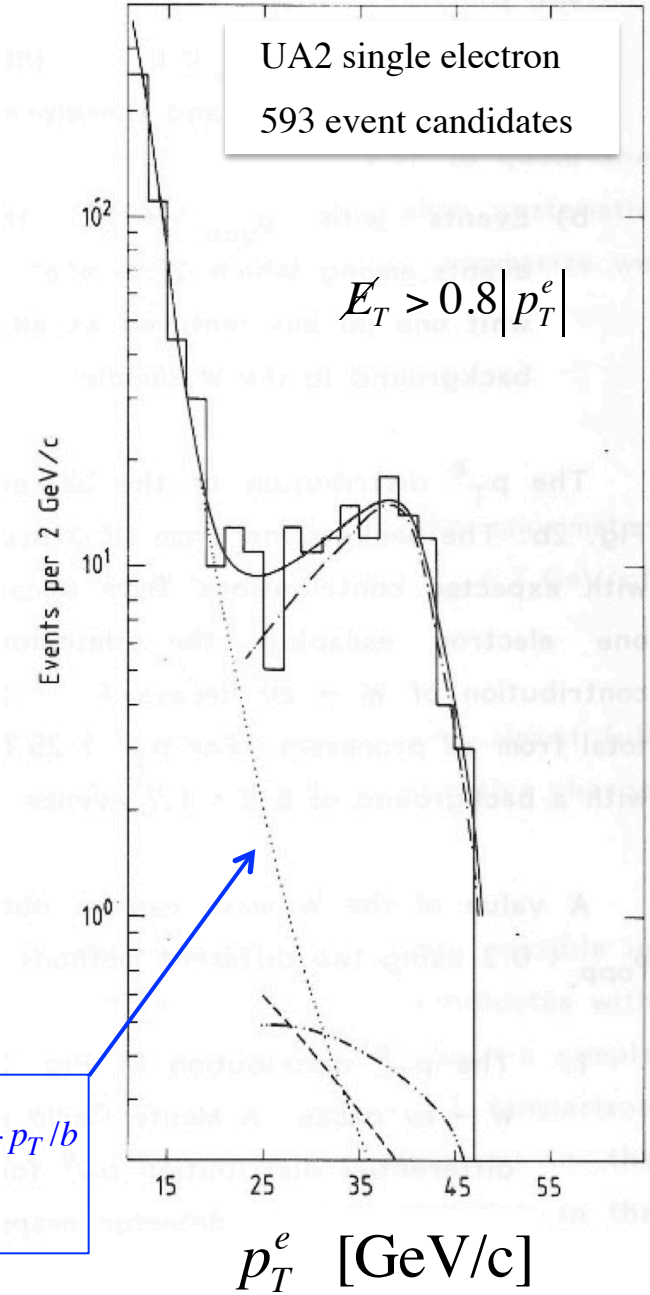
Why there were some people were studying "high-p_T" physics in the 1960's?

They were looking for a 'left handed' intermediate boson $W^{\pm}$, the proposed carrier of the weak interaction [T. D. Lee and C.-N. Yang, PRL. 4, 307 (1960)]

The $W^{\pm}$ would be visible above the background as a a peak at lepton transverse momentum

$$p_T^e \geq \frac{1}{2} M_W$$

Cocconi: $\frac{dN}{dp_T} \approx e^{-p_T/b}$



In the mean time: discovery of DIS at SLAC

Stanford Linear Accelerator Center (SLAC)

electron beams up to 20 GeV.

First results in 1968 – discovery of DIS.

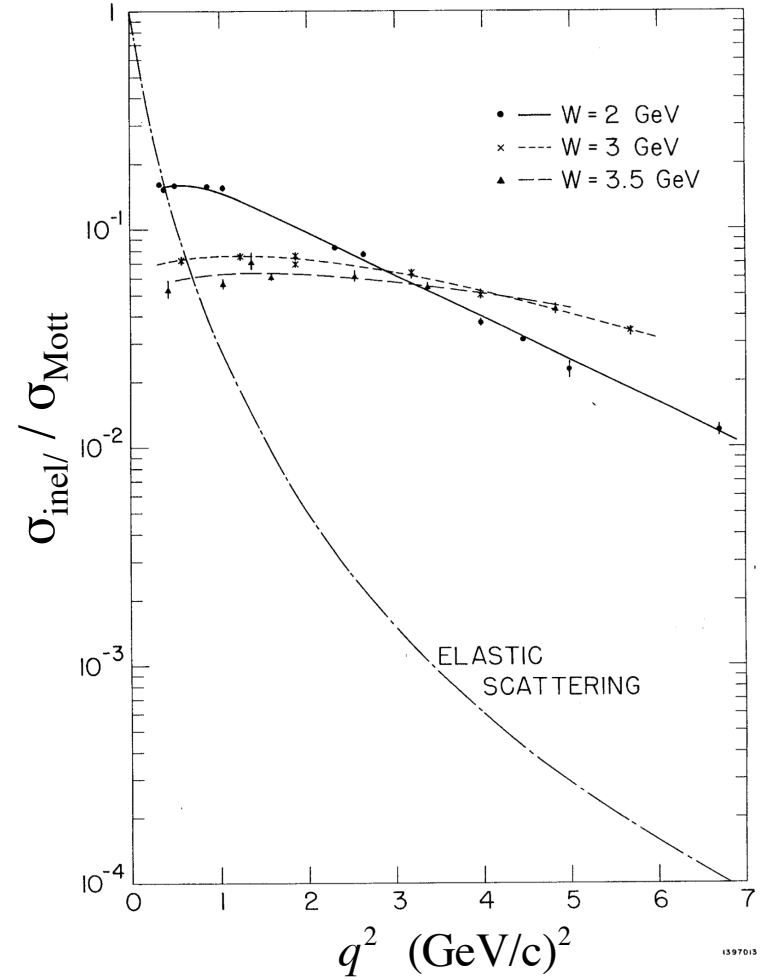
- Around q^2 ~1 GeV/c elastic and inelastic cross sections are about equal.
- Above q^2 ~1 GeV/c σ_{el} drops significantly whereas σ_{inel} remains approx const.

1) Mott, helicity cons.

$$\left(\frac{d\sigma}{dQ^2}\right)_{\text{Mott}} = \frac{4\pi\alpha^2}{Q^4}\cos^2\theta/2$$

2) Inelastic, spin-$\frac{1}{2}$, recoil E'/E and magnetic term

$$\frac{d^2\sigma}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^4}\frac{E'}{E}\left[W_2\cos^2(\theta/2) + 2W_1\sin^2(\theta/2)\right]$$



Phys.Rev.Lett., **1969**, *23*, 935-939

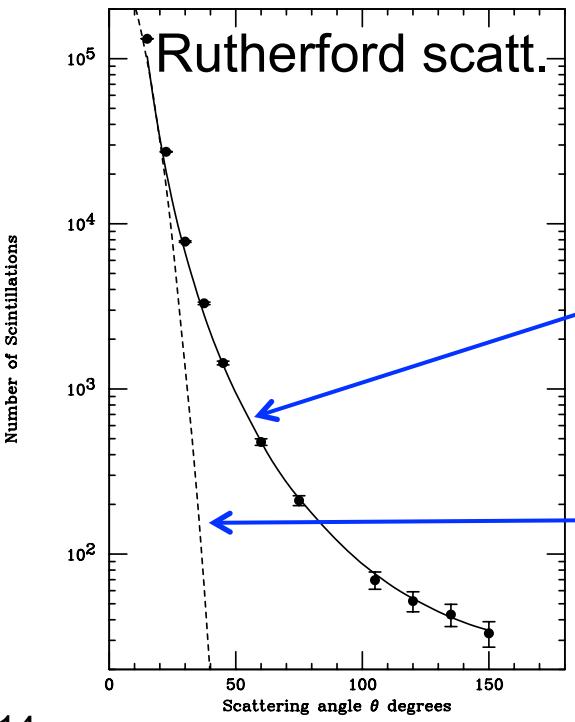
2nd : Discovery of Hard Scattering in p+p collisions

At the same time:

CERN-ISR breaking of $e^{-6\,p_T}$

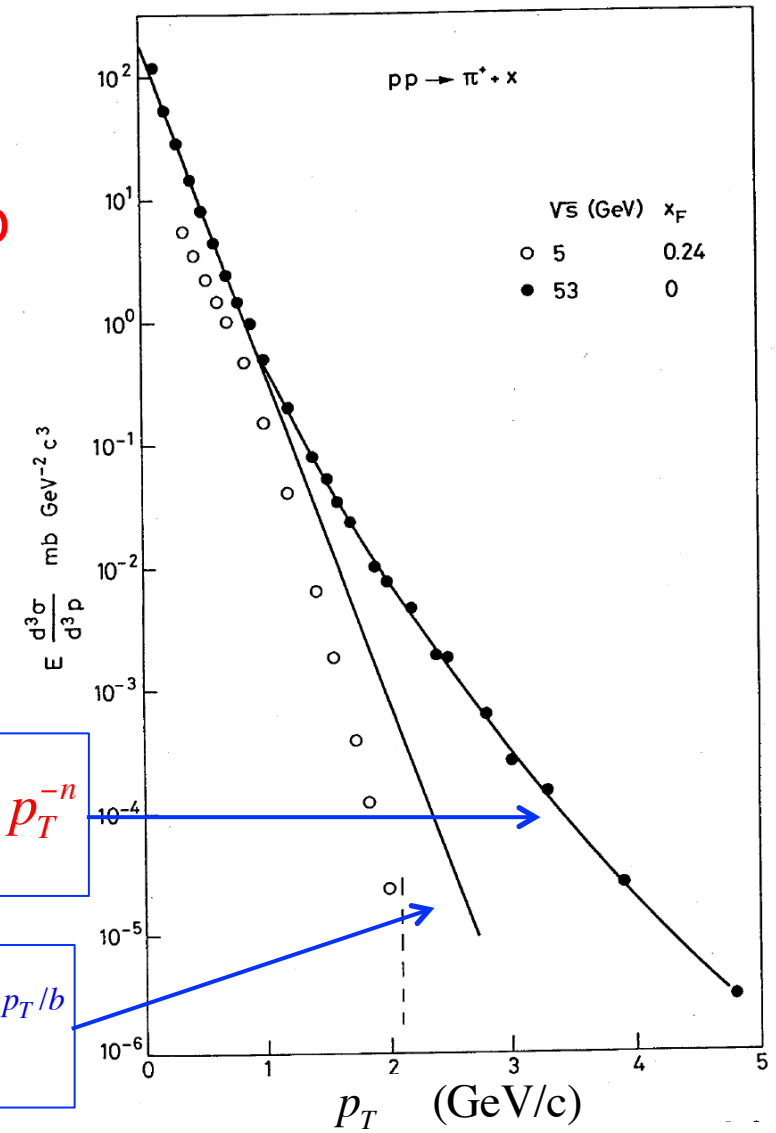
Discovery of high-p_T production in p-p

- Due to the point-like constituent (parton).
- No scale (point-like) → conformal theory
- Beginning of scaling era → QCD



Power law: $\frac{dN}{dp_T} \approx p_T^{-n}$

Cocconi: $\frac{dN}{dp_T} \approx e^{-p_T/b}$



CCR Coll. Phys. Lett. **46B**, 471 (1973)

Birth of QCD

There were 4 key experimental observations that made the composite theory of hadrons believable

1. discovery of point-like constituents in DIS
2. complementary discovery of dilepton production in p+A collisions Drell-Yan annihilation $q + \bar{q} \rightarrow \mu^+ + \mu^-$
3. observation of enhanced particle production at large p_T in p-p collisions at ISR in experiments searching for single $e^{\pm}$ from the $W^{\pm}$ decays.
4. the observation of the J/ψ at BNL-AGS and SLAC.

These discoveries turned Gell-Mann and Zweig's quarks from mere mathematical concepts to the fundamental constituents of matter ➠ QCD.

High-p_T sector ➠ pQCD

Berman, Bjorken and Kogut - Scaling era

$p + p \rightarrow a + X$ kinematics is completely fixed by the two dimensional quantities s and p_T and two angles ϕ and ϑ.

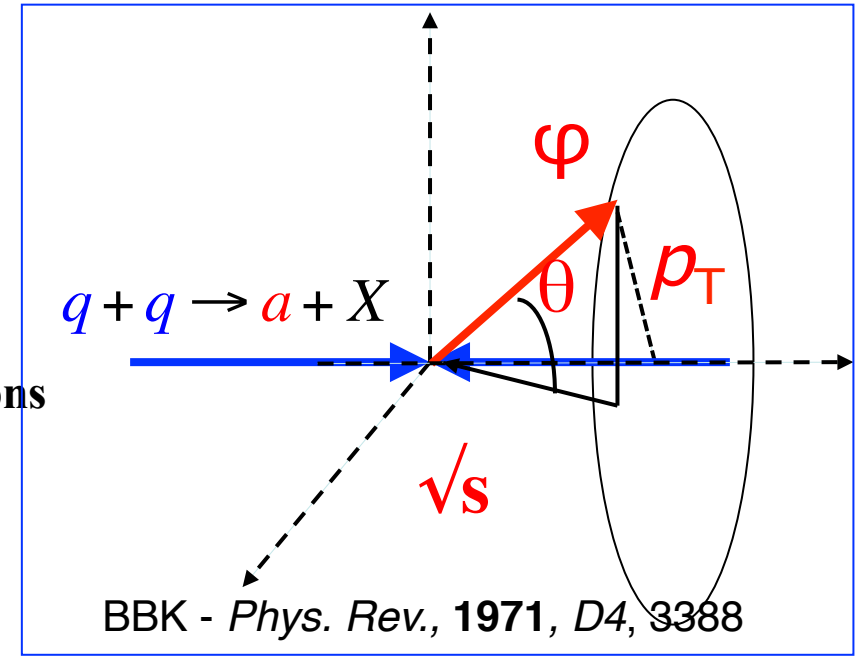
Dims of the invariant xsection

$$[\sigma]=\text{GeV}^{-2} \text{ and } \left[E\frac{d^3\sigma}{d^3p}\right]=\text{GeV}^{-4}$$

Any combination of p_T, s or x_T **preserving dimensions** yields

$$E\frac{d^3\sigma}{d^3p}=\frac{p_T^4}{s^4}g(x_T,\vartheta)=\frac{p_T^4}{256}\frac{x_T^8}{p_T^8}g(x_T,\vartheta)=\frac{1}{p_T^4}g(x_T,\vartheta)$$

$x_T \equiv 2p_T/\sqrt{s}$ rel. p_T wrt. beam mom $\sqrt{s}/2$



Conformal limit $E\frac{d^3\sigma}{d^3p} \propto \frac{1}{p_T^4}$ or $\frac{1}{\sqrt{s}^{n=4}}g(x_T,\vartheta)$

LO QED-like vector boson exchange (glue, γ)

$\Rightarrow$ power low p_T^{-n} with $n=4$

$g(x_T,\vartheta)$ universal $\sqrt{s}$ independent function

However

- Running $\alpha(Q^2)$
- PDF and FF scaling violation
- k_T smearing and higher-twist phenom.

$$n^{++} \rightarrow n\left(x_T,\sqrt{s}\right)$$

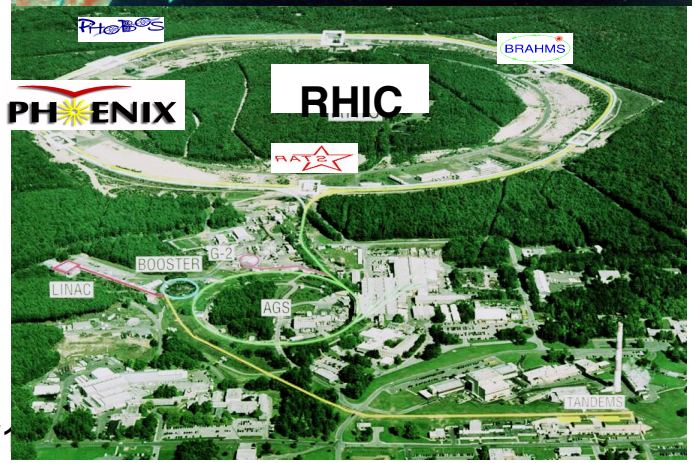
Relativistic Heavy Ion Collider

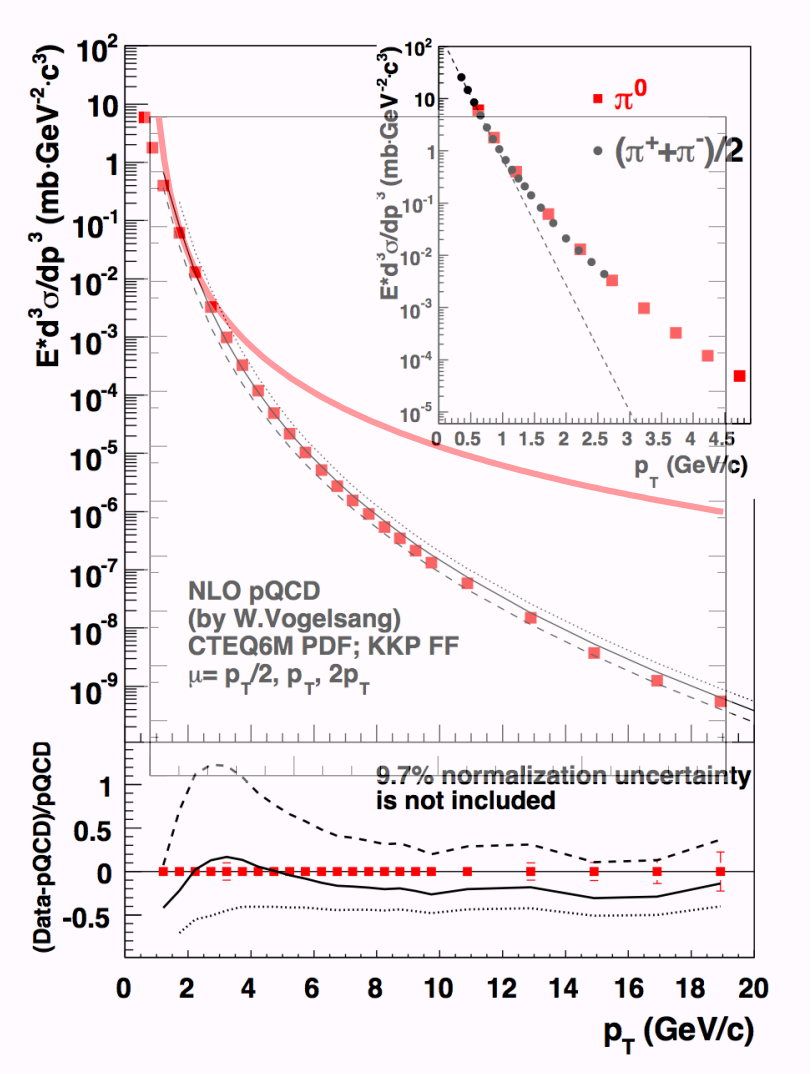
RHIC – first Heavy Ion Collider

Brookhaven Nat. Lab

$\sqrt{s}$ = 500 GeV p-p polarized

$\sqrt{s_{NN}}$= 200 GeV Au=Au





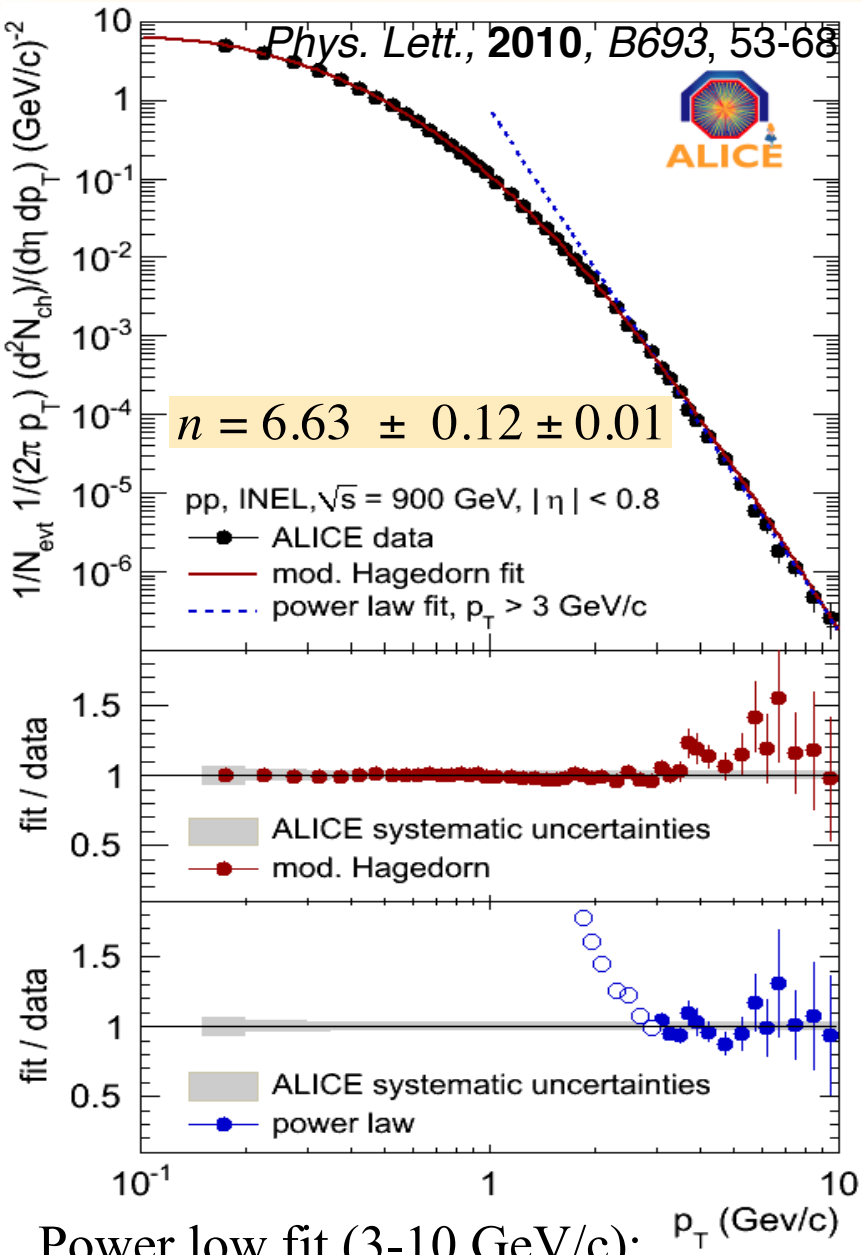
Low $p_T \sim e^{-\alpha . pT}$ α=5.56±0.02 (GeV/c)$^{-1}$

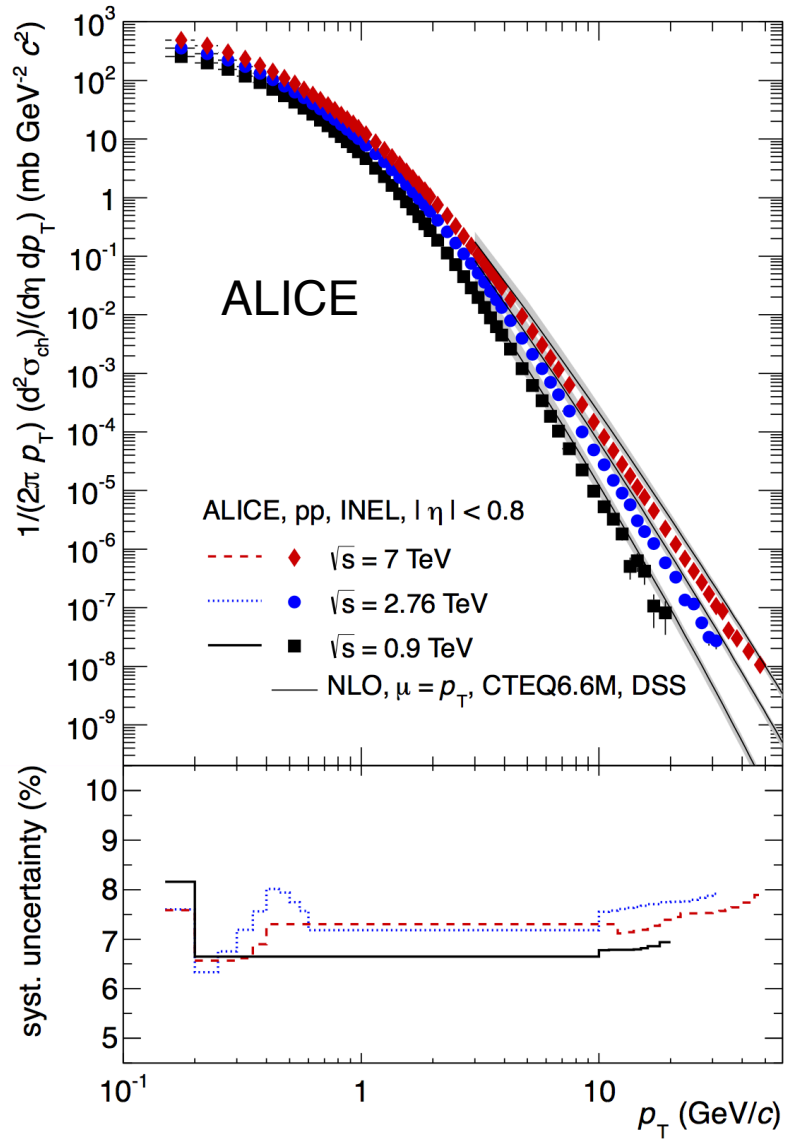
High $p_T \sim p^{-n}_T$ n=8.10±0.05 at p_T>4 GeV/c

Better then 30% agreement to NLO

PHENIX; Phys. Rev., 2007, C76, 034904

Inclusive charged distributions (INEL)





Power low fit (3-10 GeV/c):

Eur.Phys.J., **2013**, *C73*, 2662

High-p_T region → x_T scaling

No scale $E\frac{d^3\sigma}{d^3p} \propto \frac{1}{\sqrt{s}^{n++}} g(x_T)$

Prediction Arleo, Brodsky et. al. based on higher-twist dynamics. No room to discuss.

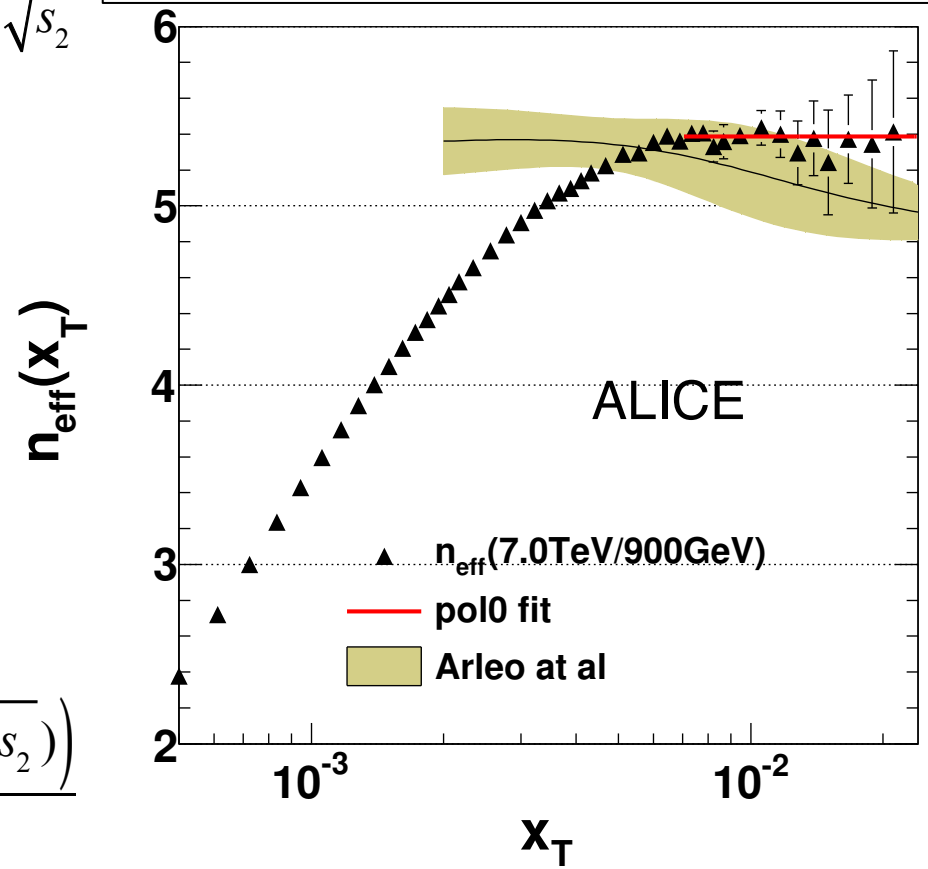
Phys. Rev. Lett., **2010**, *105*, 062002

The ratio of $E\frac{d^3\sigma}{d^3p}$ at two different $\sqrt{s_1}$ and $\sqrt{s_2}$

$g(x_T)$ cancels out

$$\left(\frac{\sqrt{s_1}}{\sqrt{s_2}}\right)^{n(x_T,\sqrt{s})} = \frac{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_2})}{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_1})} \Rightarrow$$

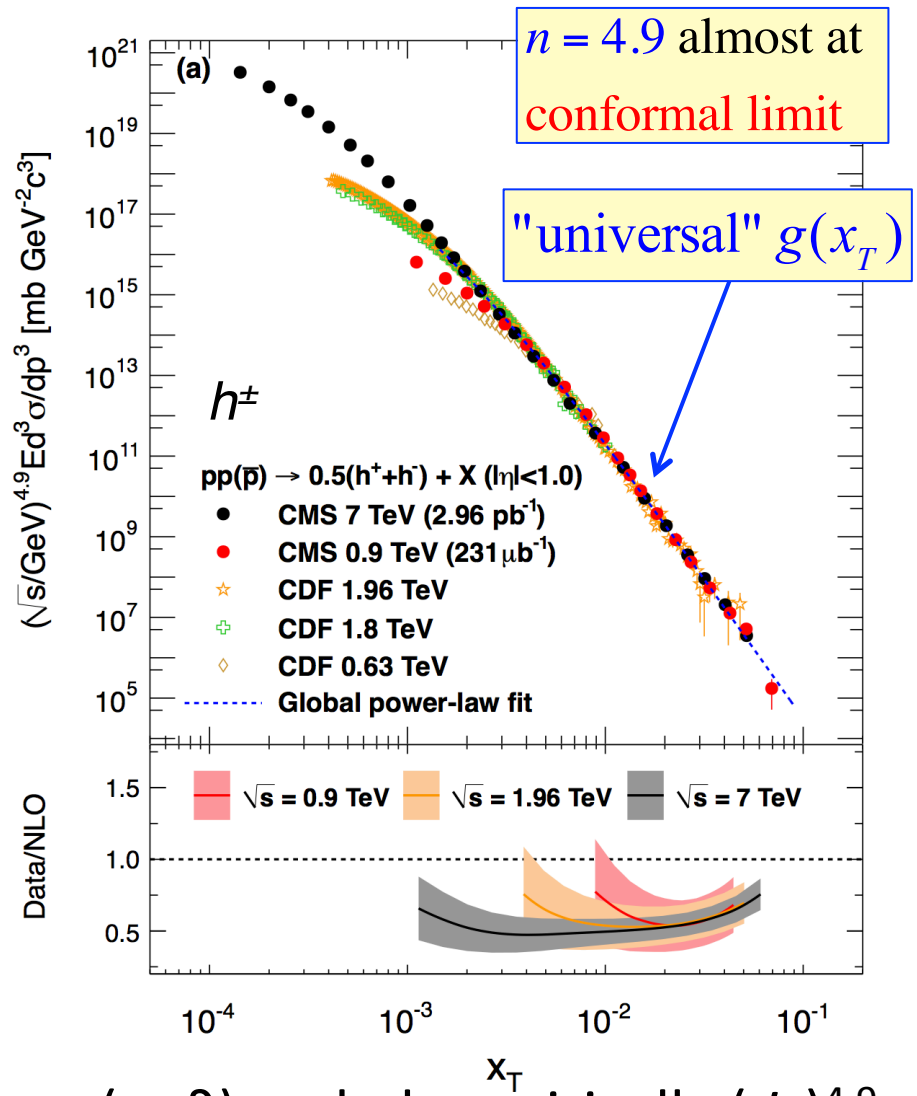
$$\Rightarrow n_{\text{eff}}(x_T) = -\frac{\ln\left(d\sigma^{\text{inv}}(x_T,\sqrt{s_1})/d\sigma^{\text{inv}}(x_T,\sqrt{s_2})\right)}{\ln(\sqrt{s_1}/\sqrt{s_2})}$$

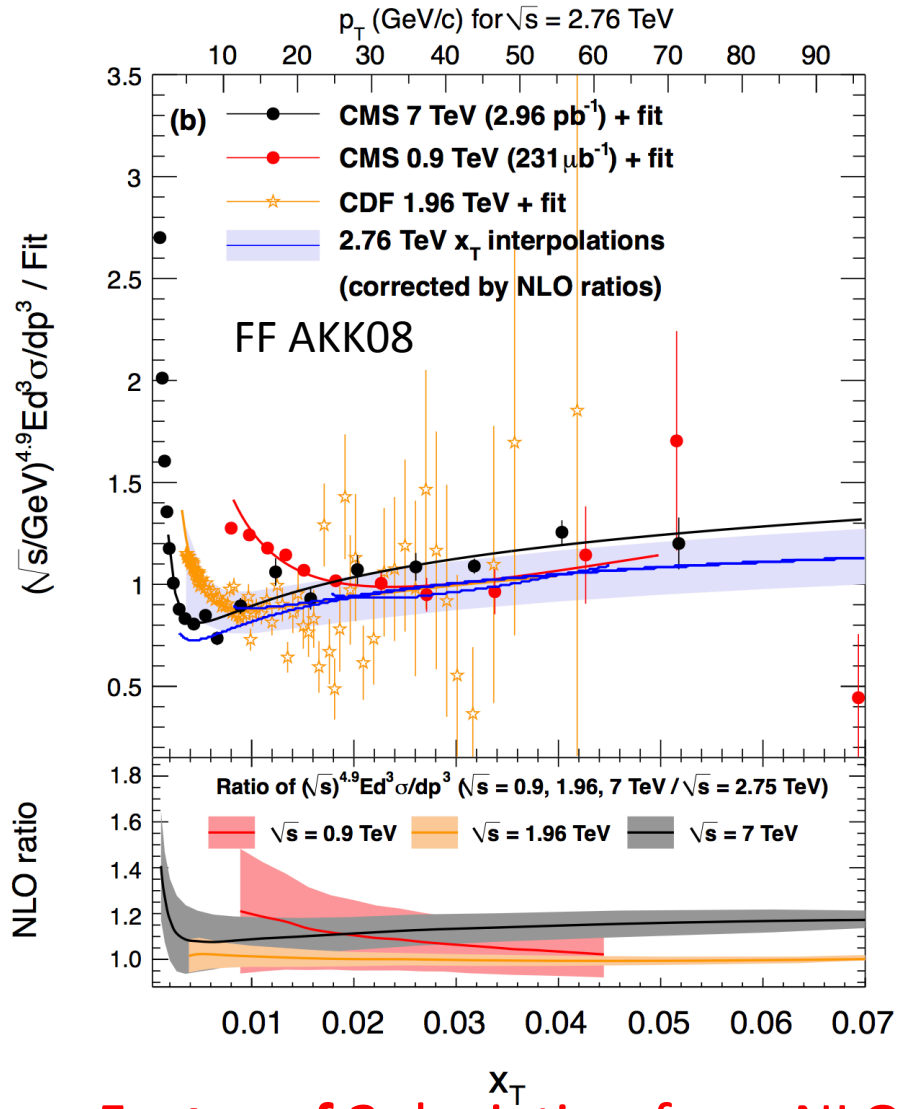


Nucl.Phys., **2011**, *A855*, 461-464

$$E\frac{d^3\sigma}{d^3p} \propto \frac{1}{\sqrt{s}^{4.9}} g(x_T), \quad x_T \equiv \frac{2p_T}{\sqrt{s}}$$

Old good x_T scaling holds at LHC





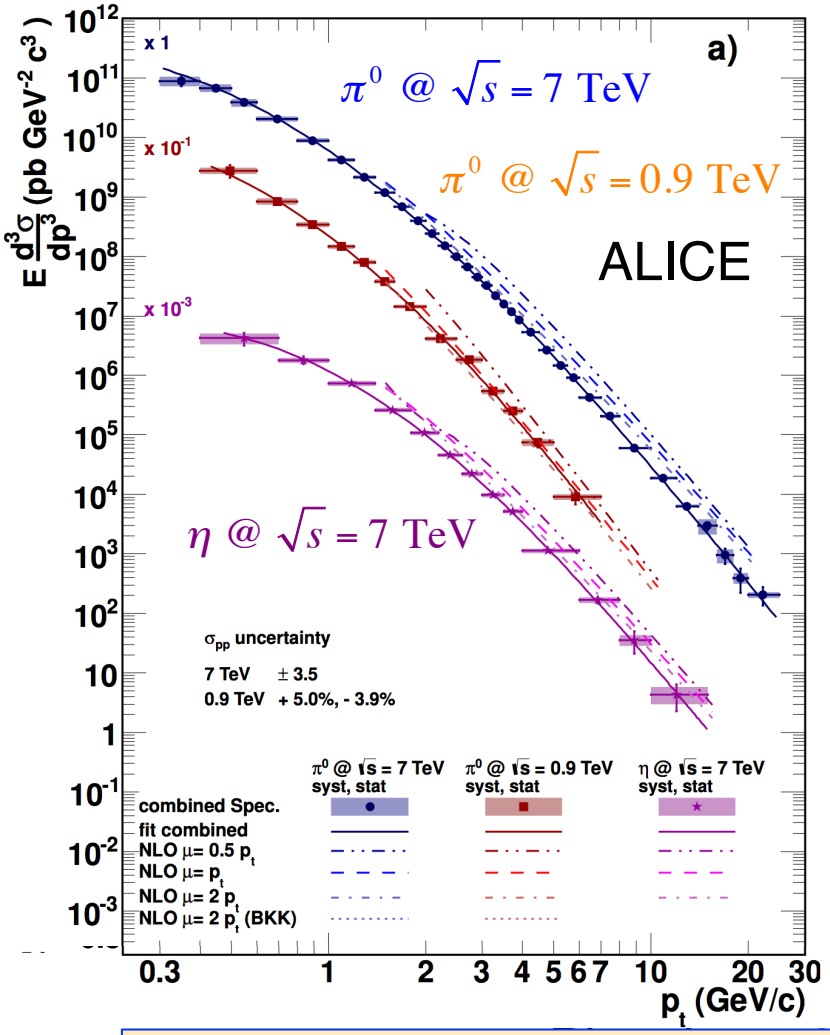
$g(x_T,\vartheta)$ scaled empirically $(\sqrt{s})^{4.9}$

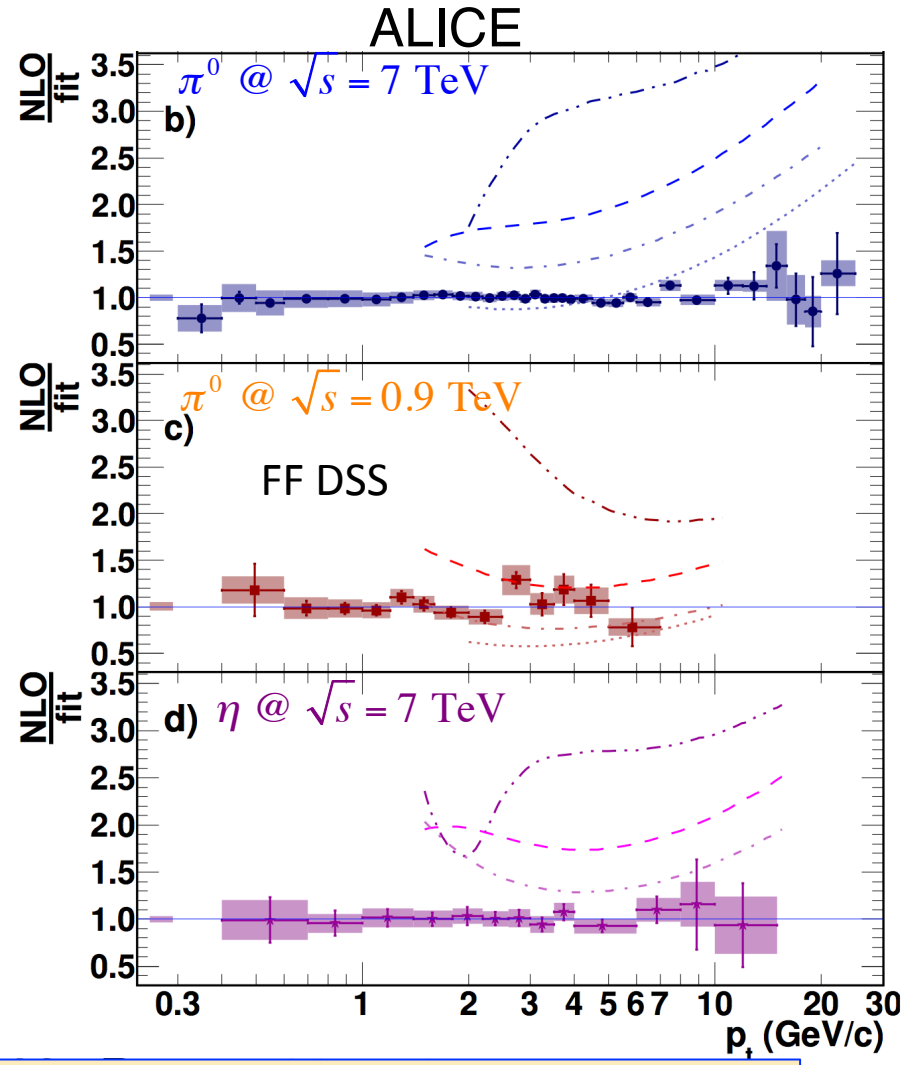
Scaling holds in $\sqrt{s}$=0.2-7 TeV !

Factor of 2 deviation from NLO

JHEP, **2011**, *1108*, 086

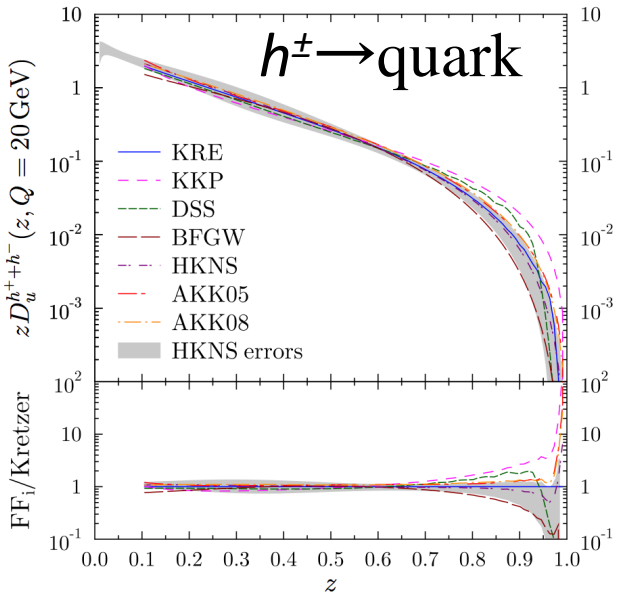
NLO doesn't work at LHC?

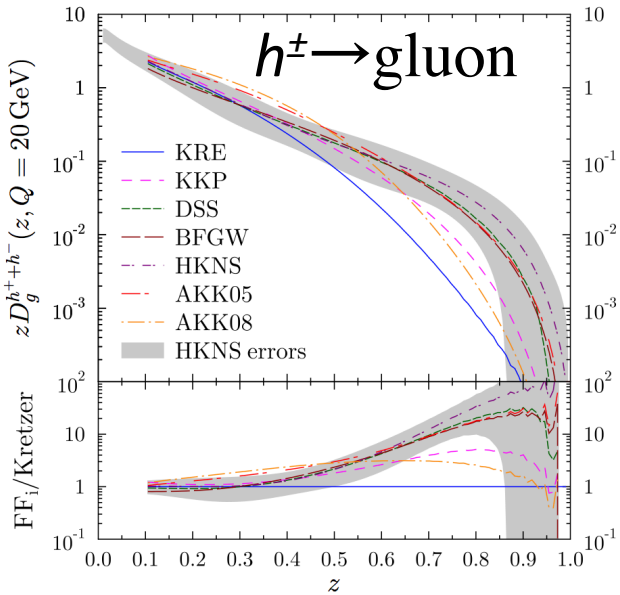


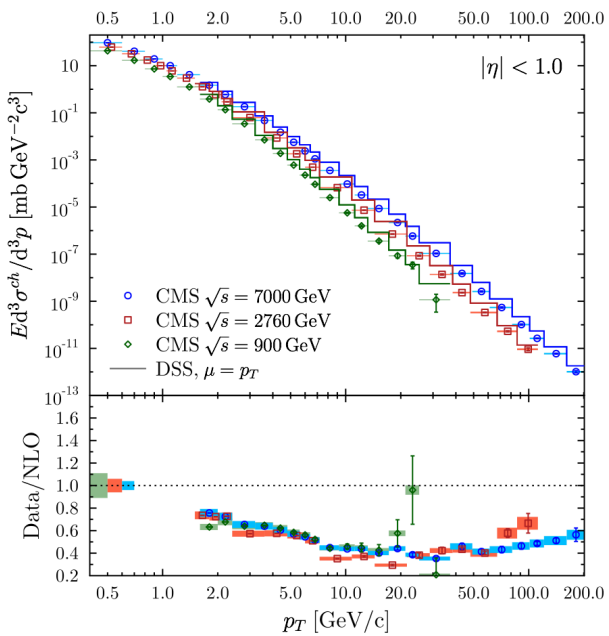


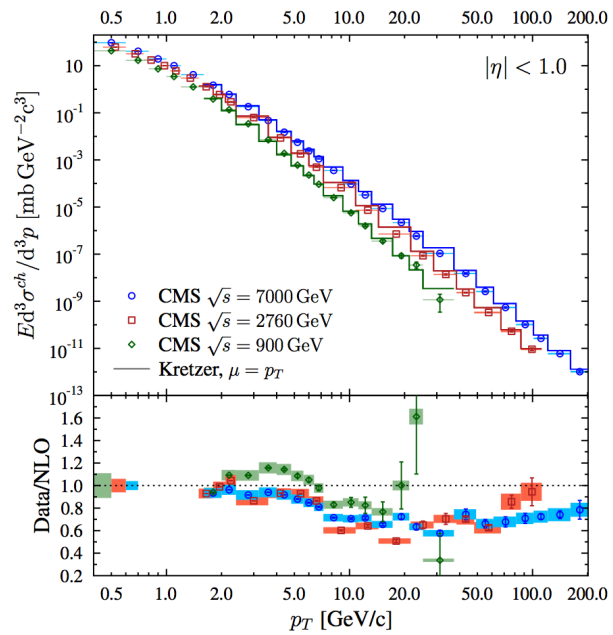
Identified particles even worse. NLO discrepancies factor >3 !
RHIC better then 30%!

NLO doesn't work at LHC?









d'Enterria, Eskola, Helenius, Paukkunen

Nucl.Phys., **2014**, *B883*, 615-628

Suspect:

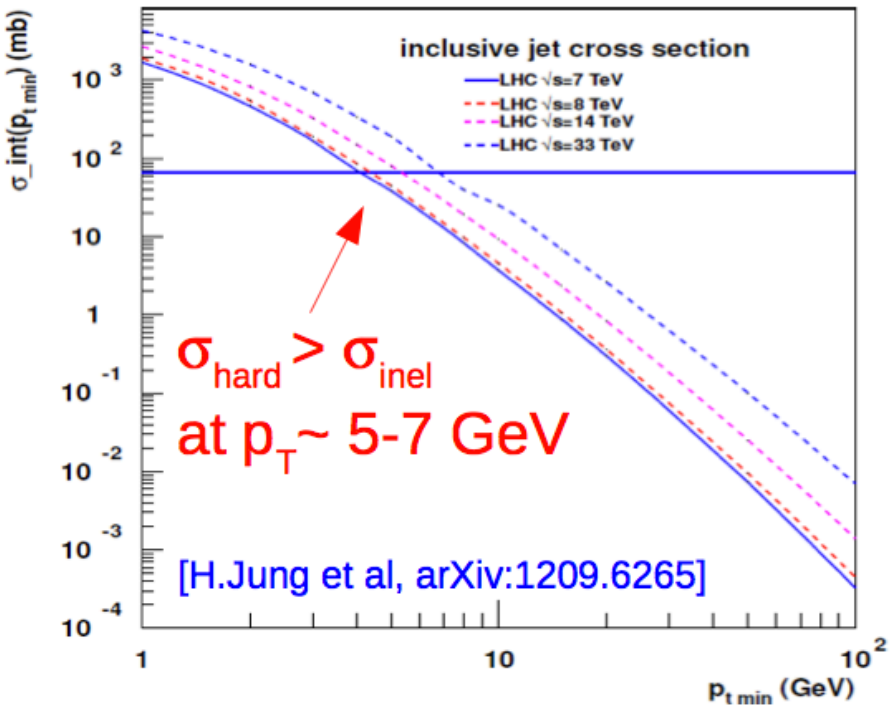
too-hard gluon-to-hadron FFs as the probable source of the problem,

Justify the need to refit the FFs using the available LHC and Tevatron data in a region of transverse momenta, $p_T > 10$ GeV/c,

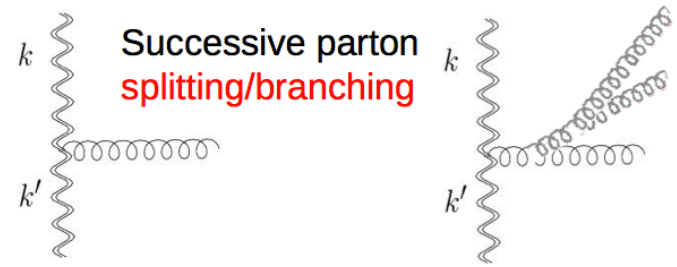
Unitarity in pQCD

pQCD (mini)jet production x-section is larger than total inelastic *p-p* x-section for p_{Tmin}~ 5-7 GeV at the LHC !

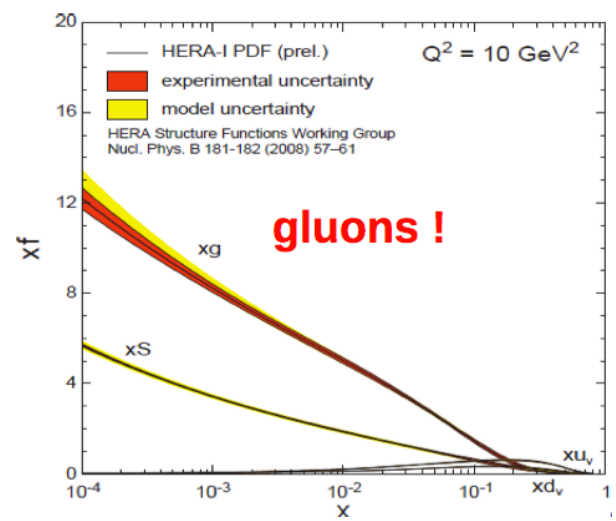
Phys.Rev., 2012, D86, 117501



DGLAP PDF evolution



Too many gluons at low *x*

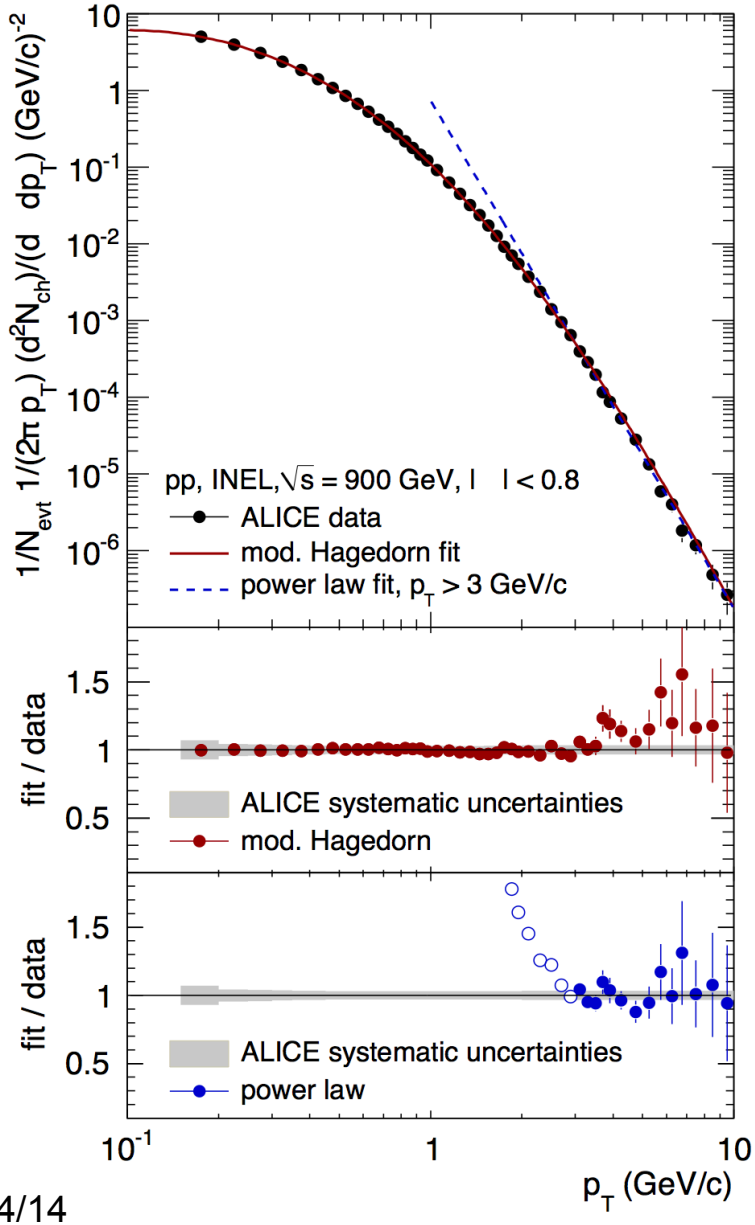


Possible solutions:

–Multi Parton Interaction

–Saturation - Color Glass Condensate – Larry MCLERRAN Thursday July 31st

high-p_T spectrum components in *p-p*



High-p_T (hard) region

- Power law exponent at LHC $h^{\pm}$ almost at the conformal limit $n=4.9$
- Old good x_T scaling holds.
- pQCD NLO seems to have more difficulties with increasing √s ?
- And violates the unitarity.

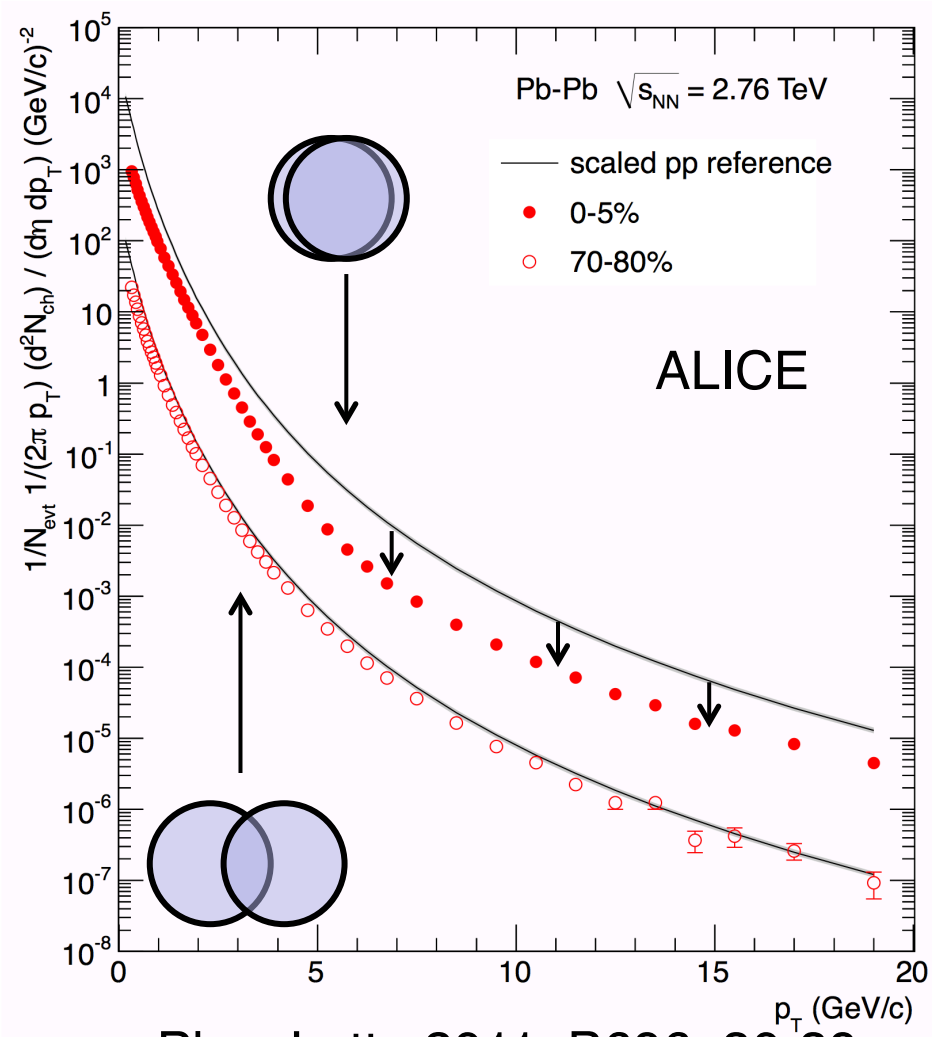
Low-p_T (soft) region

- Exponential ~exp(-6p_T) holds not only in p-p but in DIS or e^+e^- annihilation.
- Origin remains mysterious.
  Maybe due to the: "*effective event horizon introduced by the confining string, in analogy to the Hawking-Unruh effect*"

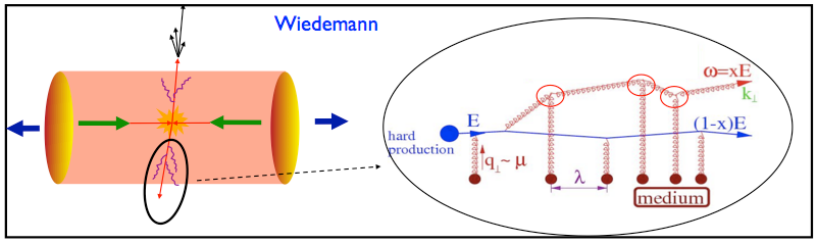
[Kharzeev at. al. arXiv:1407.4087]

Relativistic Heavy Ion Collisions

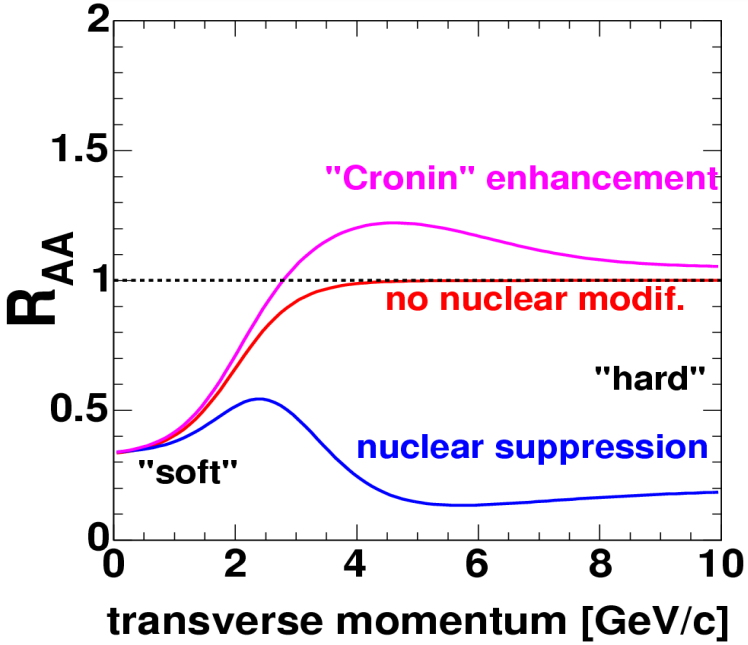
- Two discoveries based on the analysis of the high-p_T tail already discussed.
- The next discovery came from the analysis of the high-p_T yield in A-A collisions.



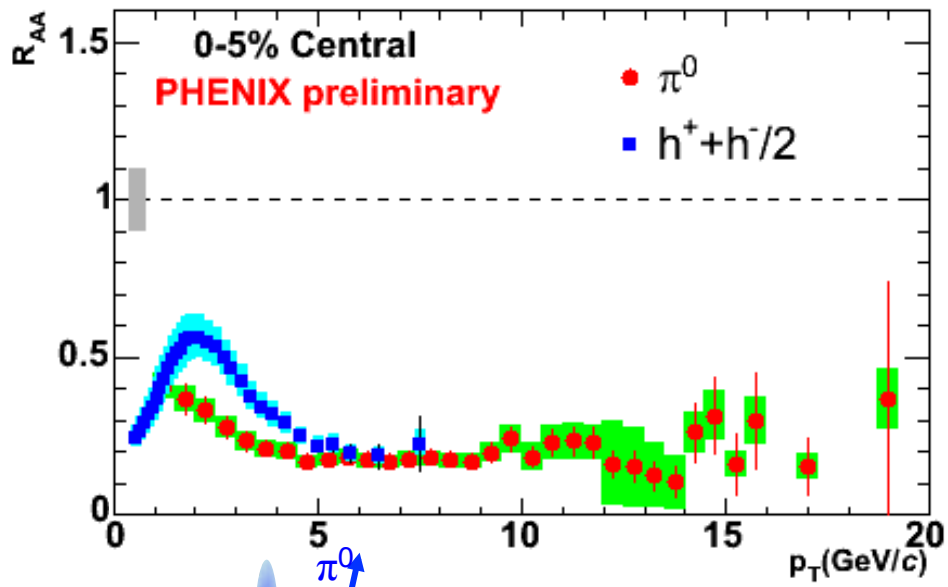
Phys.Lett., 2011, B696, 30-39

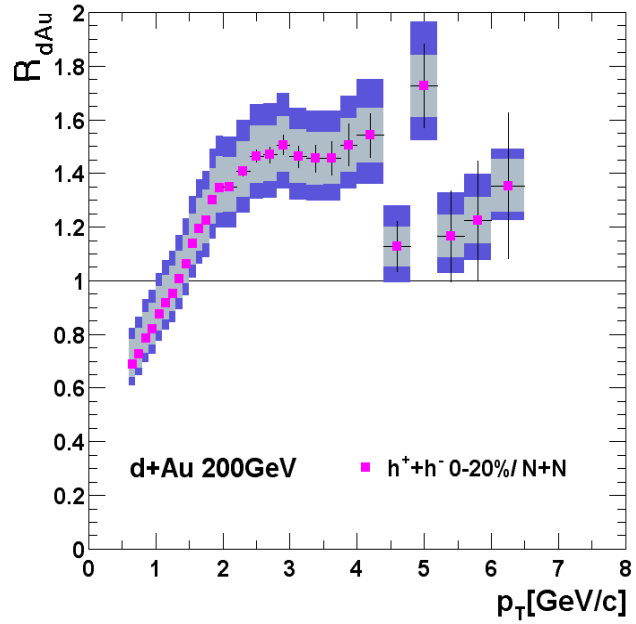


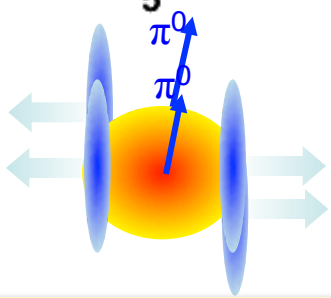
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle d^2N^{pp}/dp_T d\eta}$$

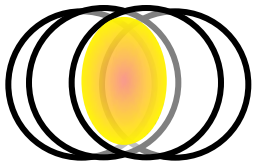


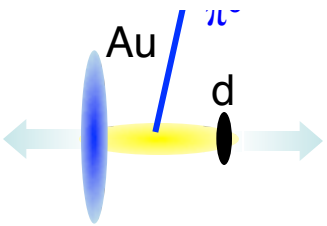
RHIC √s = 200 π^0 and h^++h^- data











1.Strong suppression (x5) in central Au+Au coll.

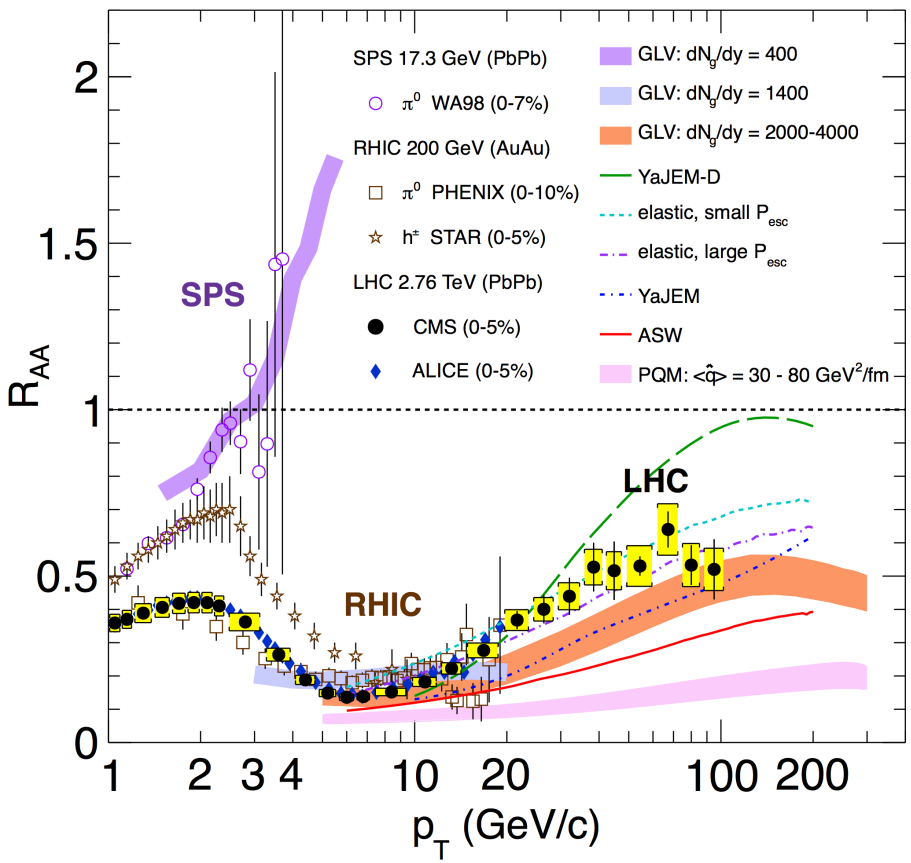
2. No suppression in peripheral Au+Au coll.

3. No suppression (Cronin enhancement) in control d+Au exp.

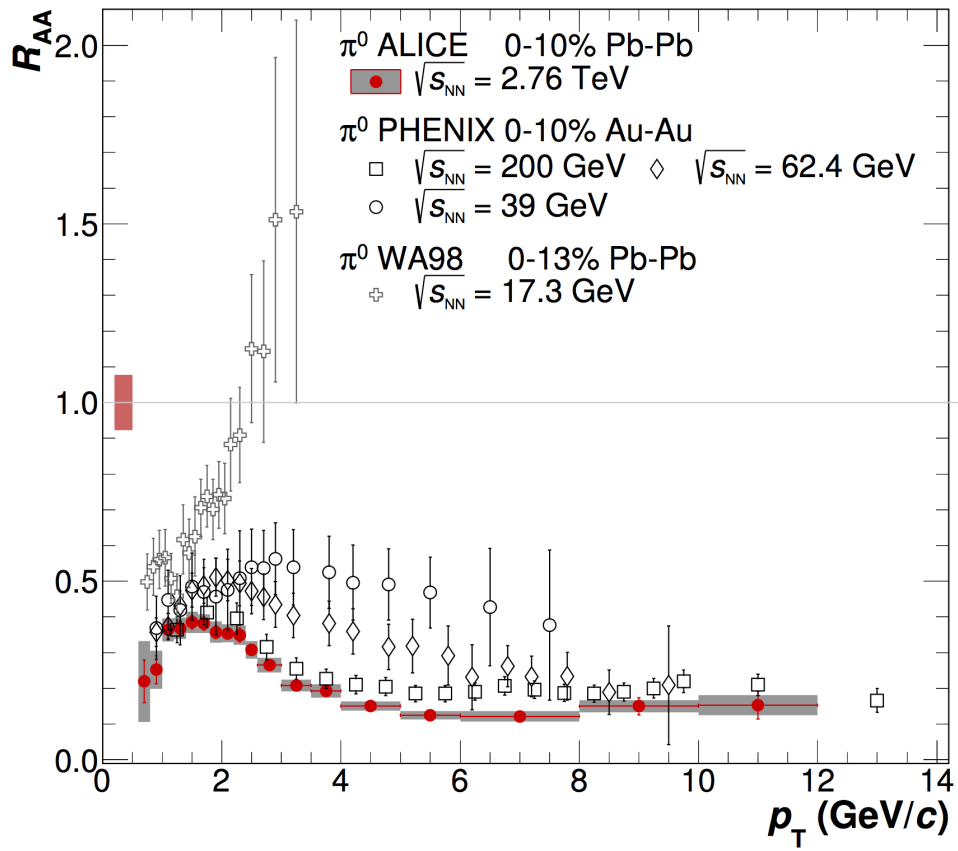
Convincing evidence for the **deconfined nuclear matter**

LHC – precise data up to p_T~100 GeV/c

The question at RHIC: is the $R_{AA}(p_T)$ const or rising with p_T ?



CMS Eur.Phys.J., 2012, C72, 1945



AICE arXiv:1405.3794

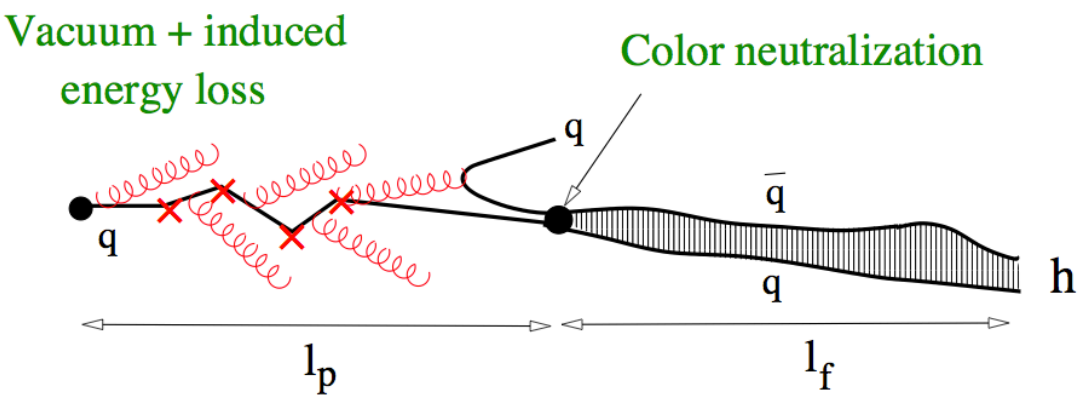
The question at LHC: does $R_{AA}(p_T)$ grow saturates or turn down?

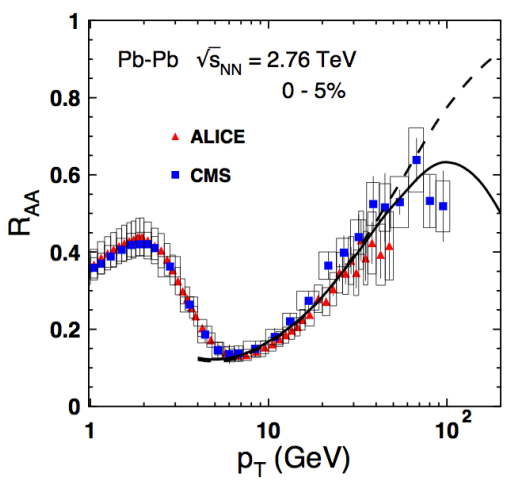
Dipole picture

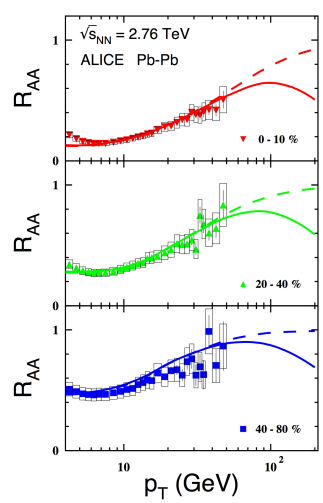
Let me pick one :

Kopeliovich, Nemchik, Potashnikova, Schmidt, "*Quenching of high-pT hadrons: Energy Loss vs Color Transparency*" *Phys.Rev.*, **2012**, *C86*, 054904

And see Boris's talk on Saturday Aug. 2nd





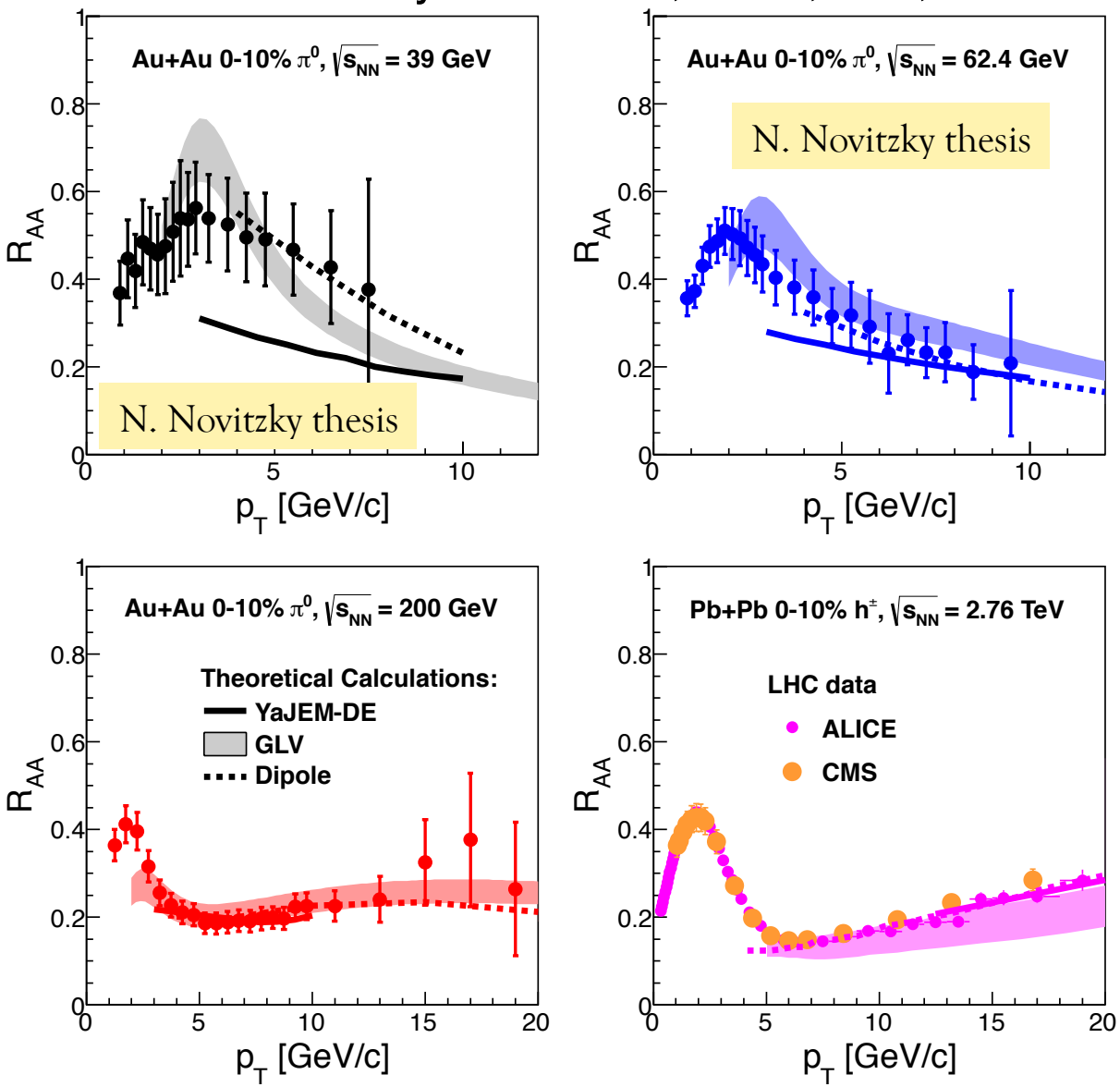


- Dipole survives even in a dense medium due to color transparency.
- However the dipole is expanding enhancing attenuation. At higher p_T expansion is Lorentz-delayed so transparency must rise with p_T.
- According this picture the R_{AA} rises due to the color transparency.
- Obviously, personal opinion, but no other model was able to describe the √s evolution so precisely

Solid lines includes an initial state interactions in nuclear collisions.

39 to 2760 GeV from RHIC to LHC!

PHENIX: Phys.Rev.Lett., 2012, 109, 152301



PhD of N. Novitzky.

R_{AA} compared to

- pQCD MC
- GLV model
- Dipole model

Quantum Coherence in action ?

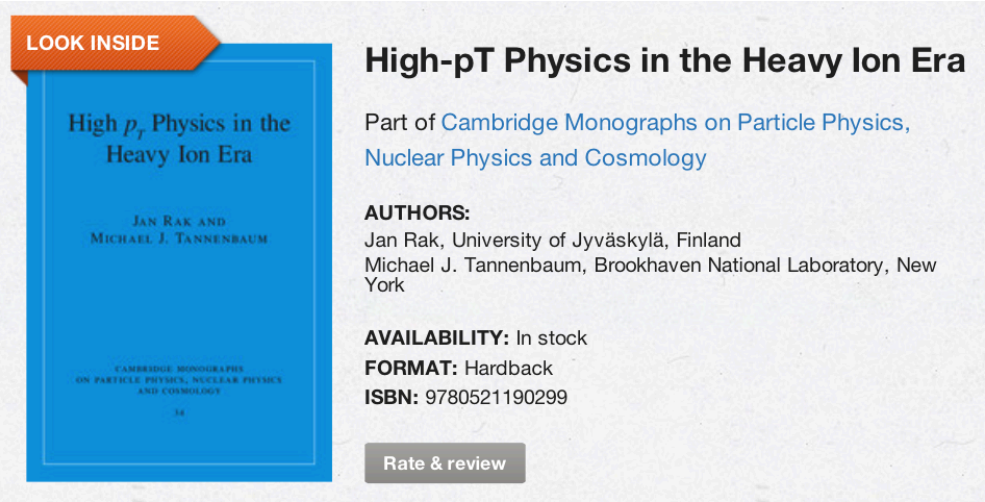
Summary

High-p_T in proton-proton collisions

- Conformal limit n=4 almost reached in $h^{\pm}$ production at LHC.
- NLO pQCD has increasing difficulties with rising $\sqrt{s}$.
- pQCD unitarity violation waiting for satisfactory resolution.

High-p_T in Heavy Ion collisions

- Deconfined nuclear medium clearly seen in the jet suppression.
- The features of R_{AA} at high-p_T very interesting program for LHC run-2.
- Color transparency and coherence in action?



backups

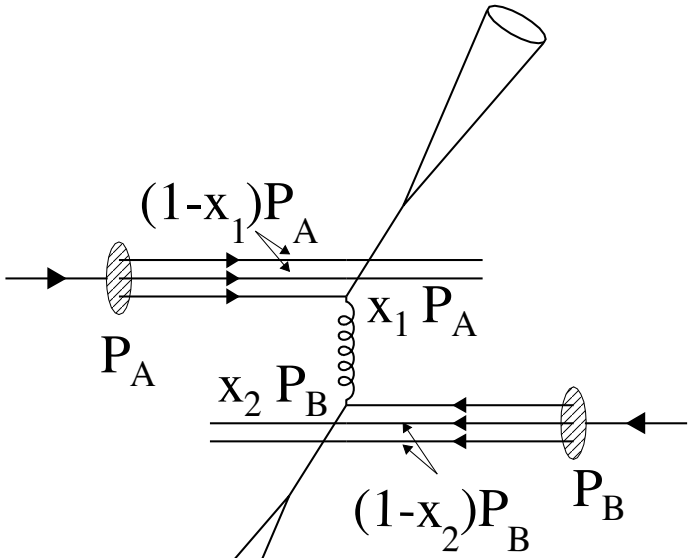
Large Transverse Momentum – Hard scattering

"Hard" means large momentum transfer, either

- a violent scatter or
- creation of a system of large mass

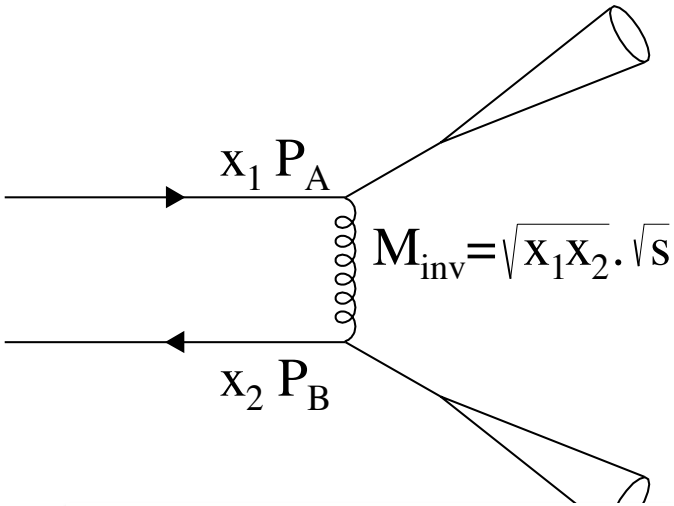
Hard scattering

- Exchange of colors
- Interaction of point-like constituents (q or g)



$x_{1,2}$ mom fractions $\hat{p}_{1,2} / P_{A,B}$

HS c.m energy $\sqrt{\hat{s}} = \sqrt{x_1 x_2}\sqrt{s}$

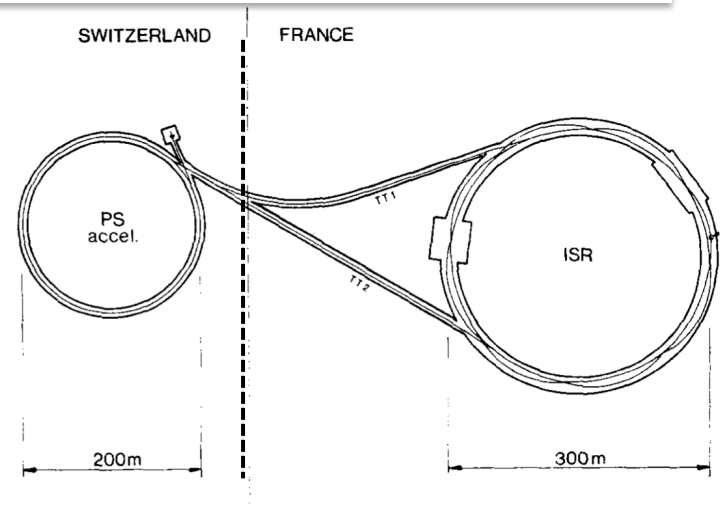


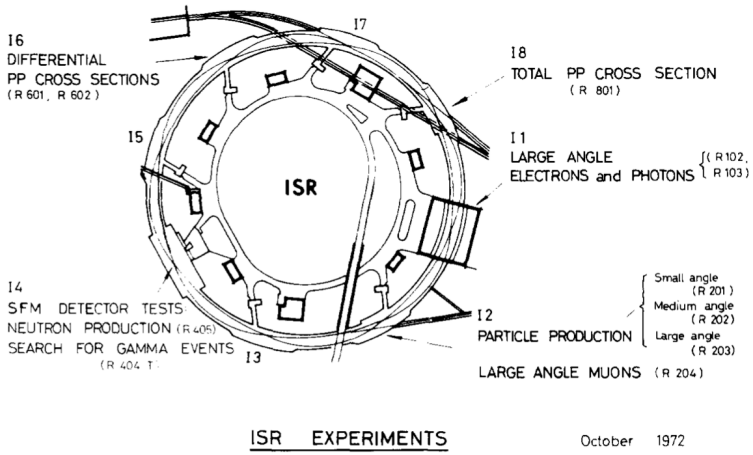
HS probes the virtual field

Early ISR era

In 1971 the CERN Intersecting Storage Rings (ISR) , being the first hadron-hadron collider, became operational. With $\sqrt{s} \sim 20\text{-}60$ GeV it was supposed to be a "next generation" as compared to the fixed target machine at Fermilab.

Intersect the Swiss/French border

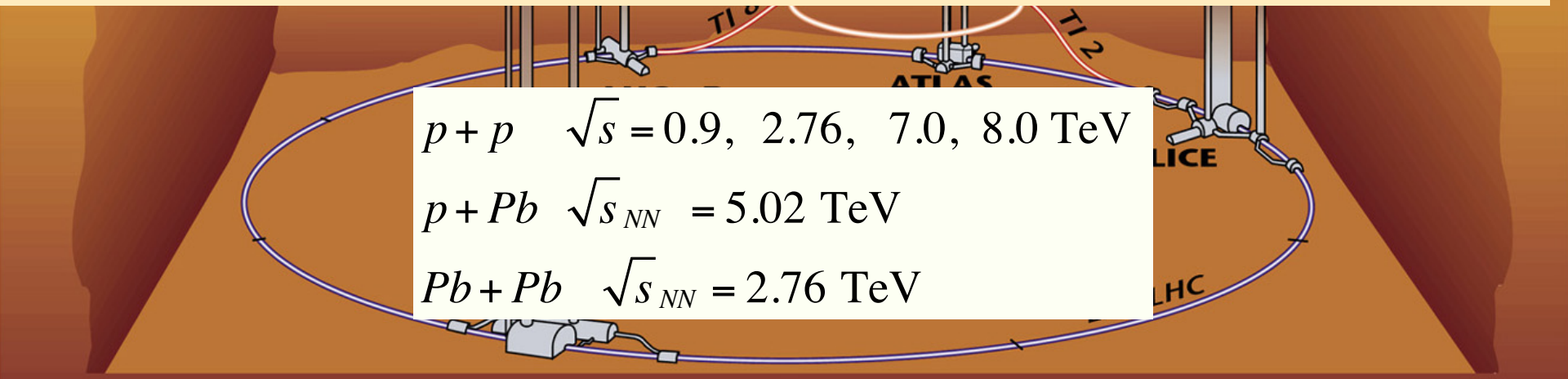




Large Hadron Collider (LHC) CERN

The physics aims of the LHC project are:

- to discover crucial missing elements of the Standard Model, namely the Higgs boson,
- search for possible new fundamental interactions,
- search for possible generations of quarks or leptons,
- search for particles responsible for the Dark Matter in the Universe
- explore the Quantum ChromoDynamics phases of matter in the Ultra-Relativistic Heavy Ion Collision (URHIC).



$$p + p \quad \sqrt{s} = 0.9,\ 2.76,\ 7.0,\ 8.0 \text{ TeV}$$

$$p + Pb \quad \sqrt{s_{NN}} = 5.02 \text{ TeV}$$

$$Pb + Pb \quad \sqrt{s_{NN}} = 2.76 \text{ TeV}$$

- Circular tunnel 27 km in circumference (old LEP). 25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch
- Design Luminosity: 10^{34}cm^{-2}s^{-1} ⇒100 fb^{-1}/year, Stored energy/beam: 350 MJ, √s up to 14 TeV