Nuclear Theory Seminar

August 7th, 2015

Inclusive Hadron Yields

LHC data, fragmentation, NNLO, and all that

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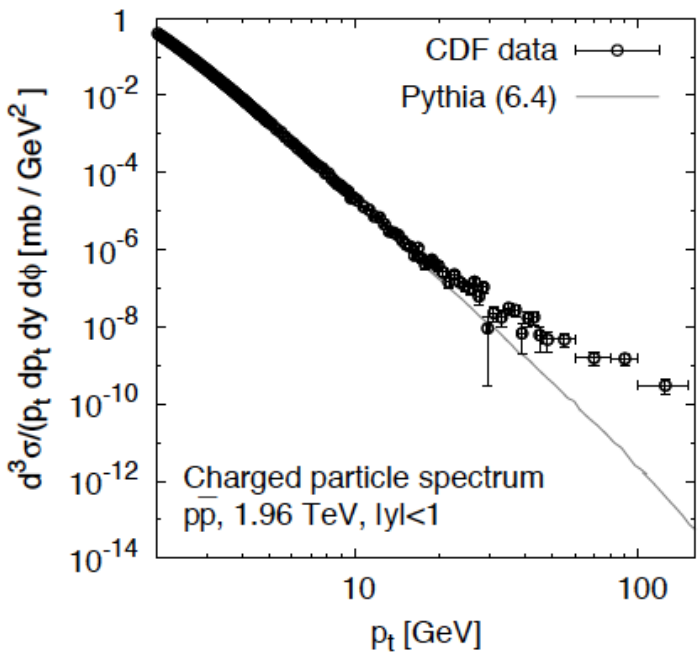
why do we care?

- ☑ non-trivial testing ground for theoretical QCD framework based on factorization
- ☑ important input in constraining hadronization of partons
- ☑ pA data may help to unravel nuclear parton densities & their limitations
- ☑ occasional (sometimes short-lived) surprises

(in)famous CDF excess of 2009



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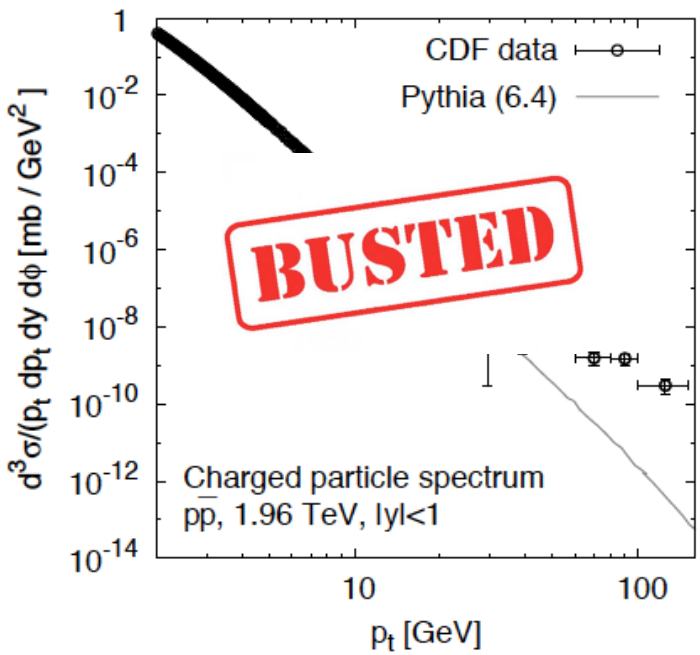

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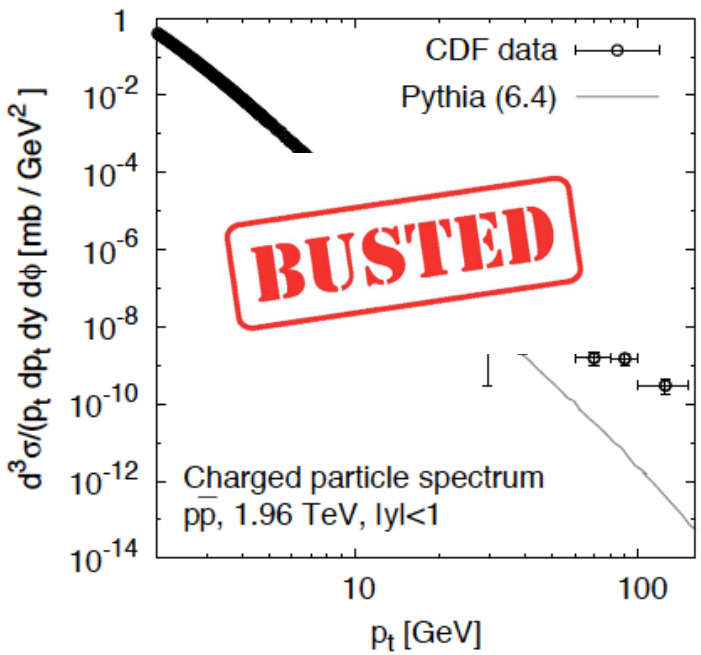
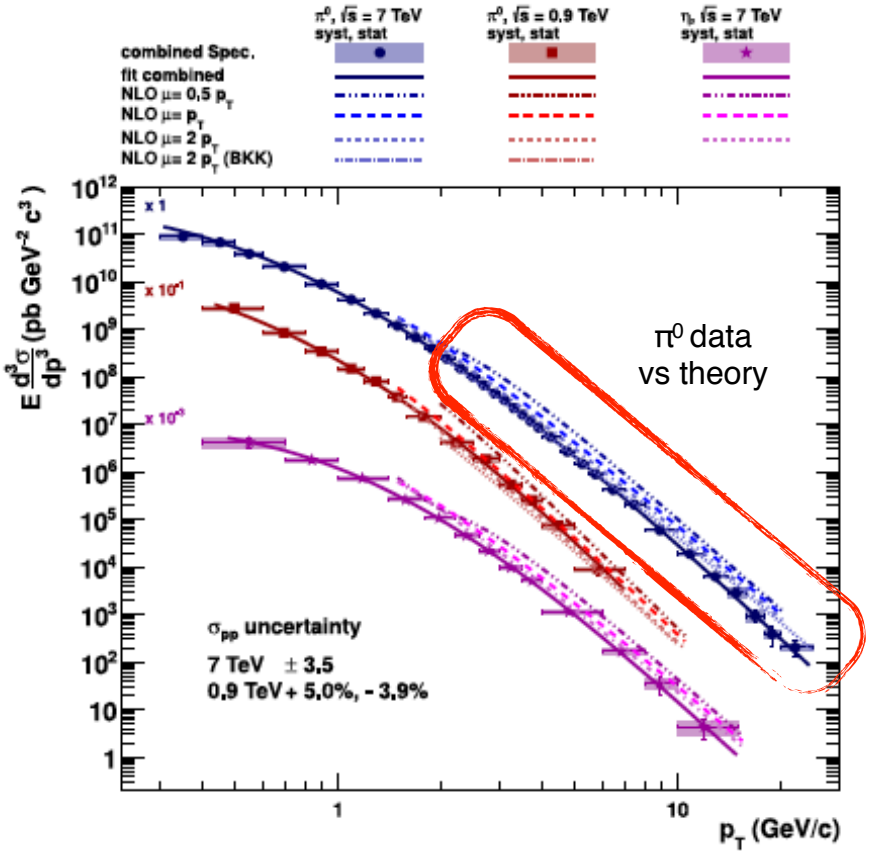


7 TeV ALICE data of 2012



topics to be covered

1

pp & pA cross section basics

4

attempts to describe pA data

3

fragmentation functions

2

phenomenology of inclusive hadrons

5

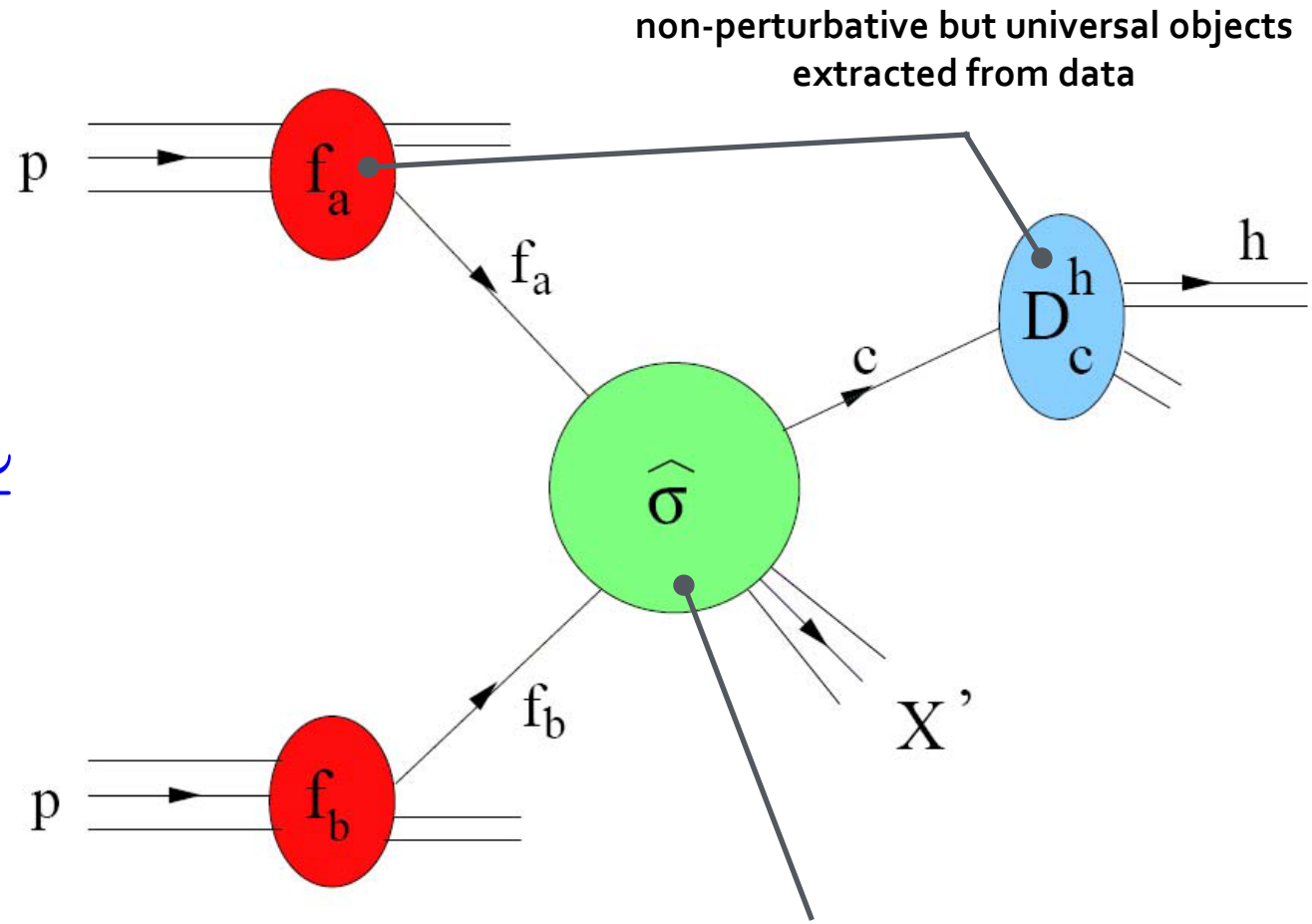
theoretical developments

key assumption: factorization

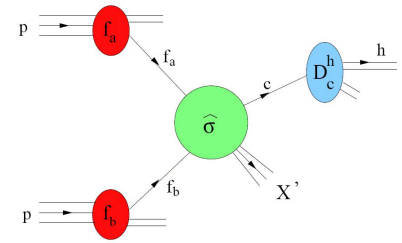
the general strategy is simple, e.g., pp —> hadron X …

measurable

$$E\frac{d^3\sigma}{dp^3} \simeq$$



factorization cont'd



… the details can be messy

Libby, Sterman; Ellis et al.; Amati et al.; Collins et al.;…

universal **long-distance physics**

μ–dep. predicted by pQCD

$$\frac{d\sigma^{pp\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, f_a(x_a,\mu_f)\, f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu'_f)$$

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short-distance physics

calculable in pQCD as series in α_s

- **valid only if p_T (= hard scale) is ``large enough" (α_s small) - but where precisely ?**

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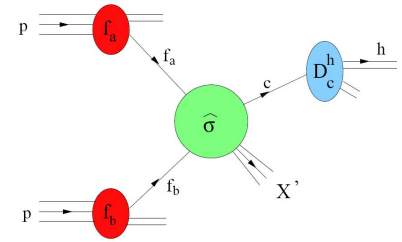

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usually safely neglected

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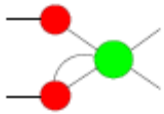

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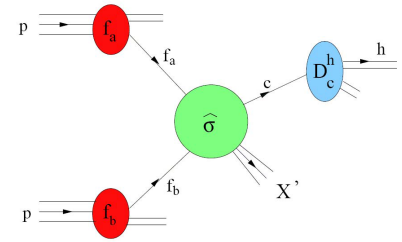

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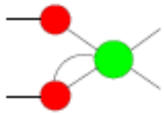
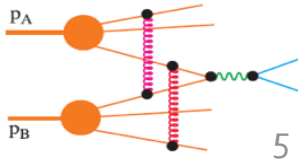
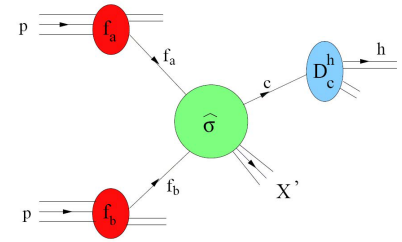


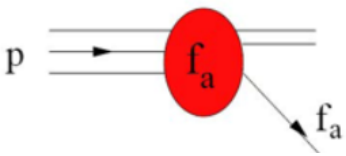
- **introduces unphysical scales $\mu_{r,f,f'}$ —> source for theoretical uncertainties**
- **faith in factorization rests in its success rather than proofs (except for DIS & DY)**



non-perturbative ingredients



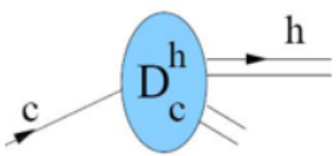
☑ parton distribution functions (PDFs)



"probability" for finding a parton "a" with momentum fraction x at a scale μ in a proton

- extracting PDFs from data has become an ``industry": CTEQ, MMHT, NNPDF, ABM, ...
- fairly well constrained over the past 30+ years

☑ fragmentation functions (FFs)



"probability" for finding a hadron "h" with momentum fraction z at a scale μ in a parton "c"

- equally fundamental but much less well known than PDFs (best for pions, less for kaons, ...)
- much fewer "brands" : AKK, HKNS, DSS

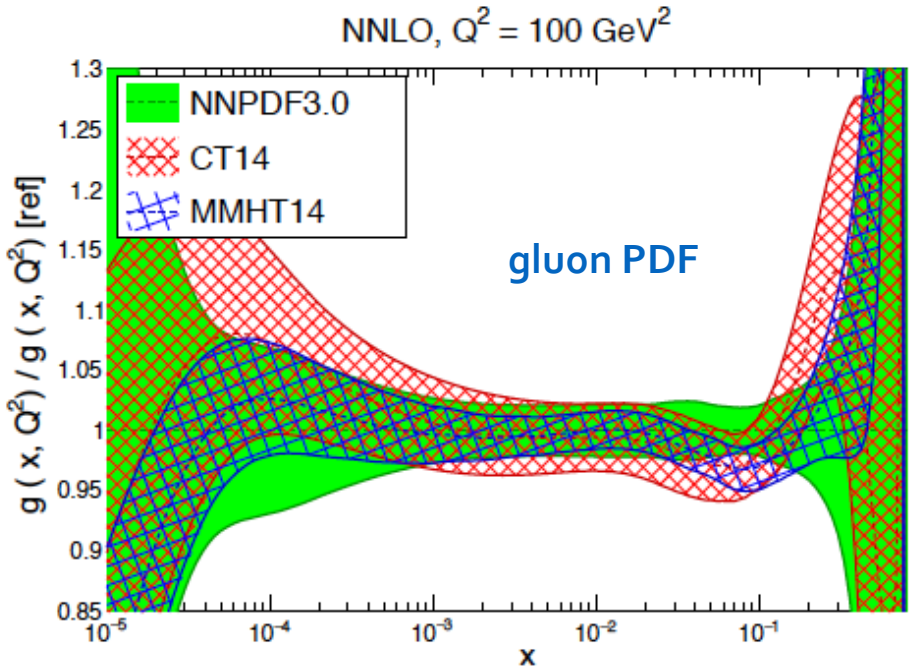
both are determined from global QCD fits to data

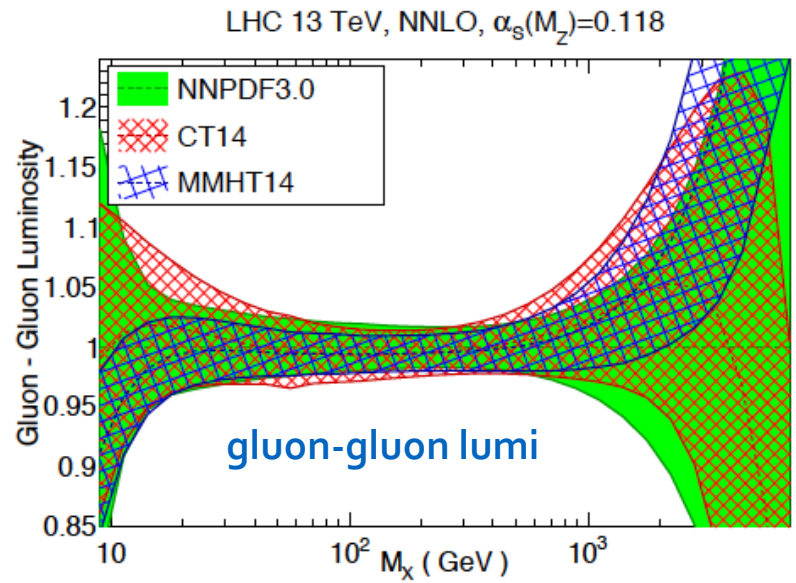
status of PDFs

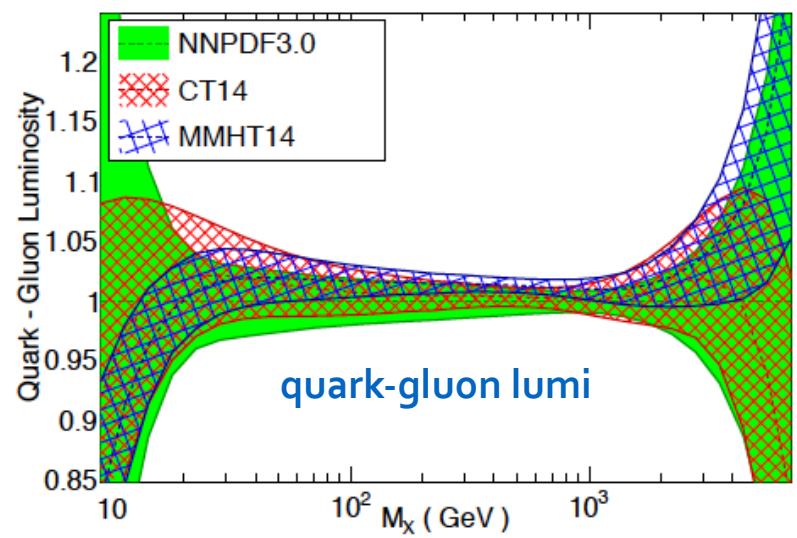
latest recommendations: PDF4LHC working group 1507.00556

☑ recent convergence of different fits

central values and uncertainties







for most purposes at the LHC
PDF uncertainties are "just a few percent"

pp —> pA : what is supposed to change?

main assumption:

keep standard pQCD framework and
assume factorization also for heavy nuclei

$$\frac{\mathbf{d}\sigma}{\mathbf{dp_T}} = \sum_{\mathbf{ab}} \mathbf{f_a}(\mathbf{x_a}, \mu) \otimes \mathbf{f_b}(\mathbf{x_b}, \mu) \otimes \mathbf{d}\hat{\sigma}_{\mathbf{ab}}(\mu) + \mathcal{O}(\frac{\mathbf{1}}{\mathbf{p_T^n}})$$

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consequences:

- **dictates use of same DGLAP scale evolution & hard scattering cross sections as in pp**

all nuclear effects are universally absorbed into a set of non-perturbative nPDFs independent of the hard probe

- **very restrictive framework as in pp —> testable predictions**
- **we know even less about validity of factorization assumption**

pQCD in pA : potential problems & limitations

- nPDFs much much much much much much less constrained than free proton PDFs
  - most active group EPS; other efforts: nCTEQ, DSSZ, ...

    —> want to use RHIC & LHC pA data to learn more !

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- what about nuclear modifications of final state?
  - known to be large for hadron multiplicities in eA scattering (HERMES)
  - FFs are vacuum matrix elements —> don't dependent on target —> same in pp and pA

    Collins, Soper '81, '83

$$D(z) \simeq \int dy^- e^{iP^+/zy^-} \mathrm{Tr}\gamma^+ \langle 0| \psi(y^-) |hX\rangle \langle hX| \overline{\psi}(0) |0\rangle$$

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- validity of factorization?
  - if at all, limited to high p_T observables (excludes many interesting "soft" observables in pA & AA)
  - potential non-linear effects in nuclei —> expect breakdown of DGLAP evolution (but where?)
  - other frameworks like color glass likely more appropriate, in particular, for AA scattering

    —> goal: map out kinematics where standard pQCD framework works & transition to non-linear dense regime

single-inclusive hadrons @ NLO in a nutshell

Nuclear Physics B327 (1989) 105–143
North-Holland, Amsterdam

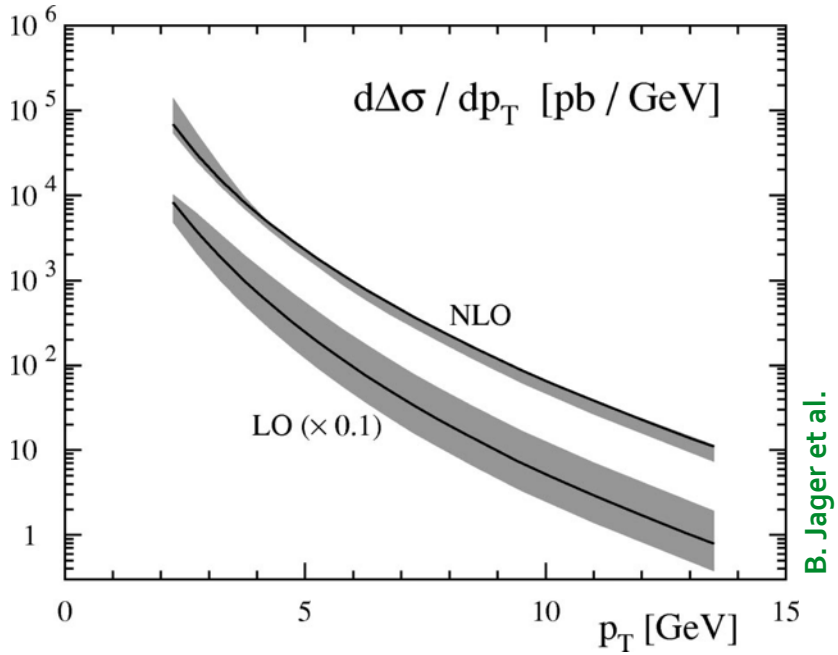
QCD CORRECTIONS TO PARTON–PARTON SCATTERING PROCESSES

F. AVERSA*, P. CHIAPPETTA, M. GRECO*, J.Ph. GUILLET**

- ☑ NLO calculation dates back to classic QCD paper in 1989

checked and extended (polarization): B. Jager, A. Schafer, MS, W. Vogelsang, PRD67 (2003) — very fast, largely analytic code
D. de Florian, PRD67 (2003) — MC code

used for current applications to LHC data and in global fits of FFs



B. Jager et al.

- ☑ find anticipated reduction in scale ambiguity

<— example from RHIC for polarized pp collisions

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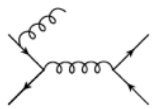
16 different channels



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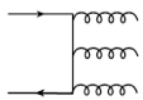

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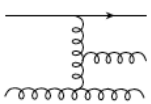

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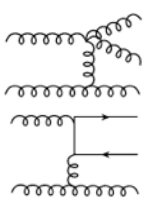

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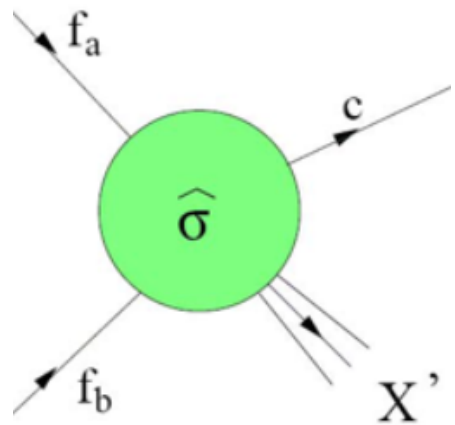

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16 different channels

final state parton which fragments into observed hadron

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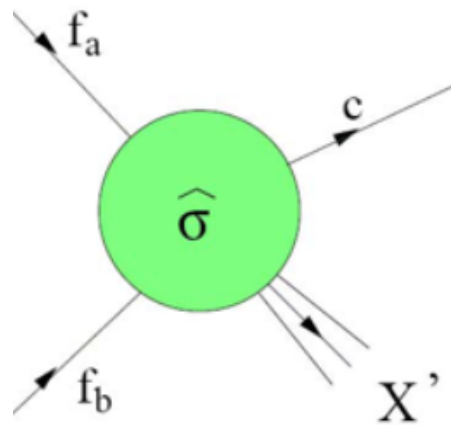

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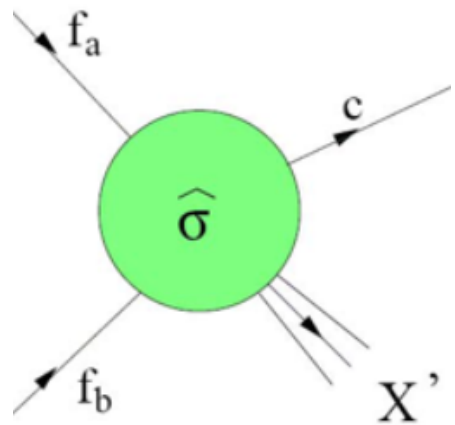

up to 2 unresolved partons analytically integrated over phase phase

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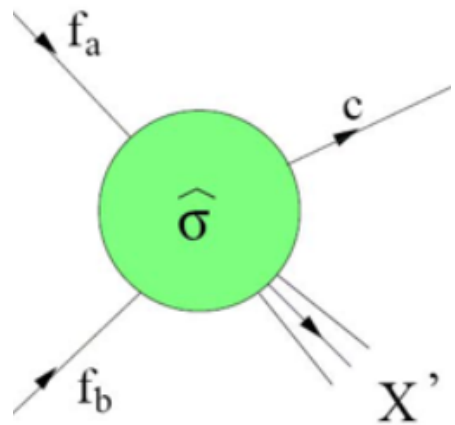


result does not apply to "leading hadron" cross sections loved by experimentalist but theoretically ill defined

NLO is still the state-of-the art for hadron production but NNLO is on the horizon

up to 2 unresolved partons analytically integrated over phase phase

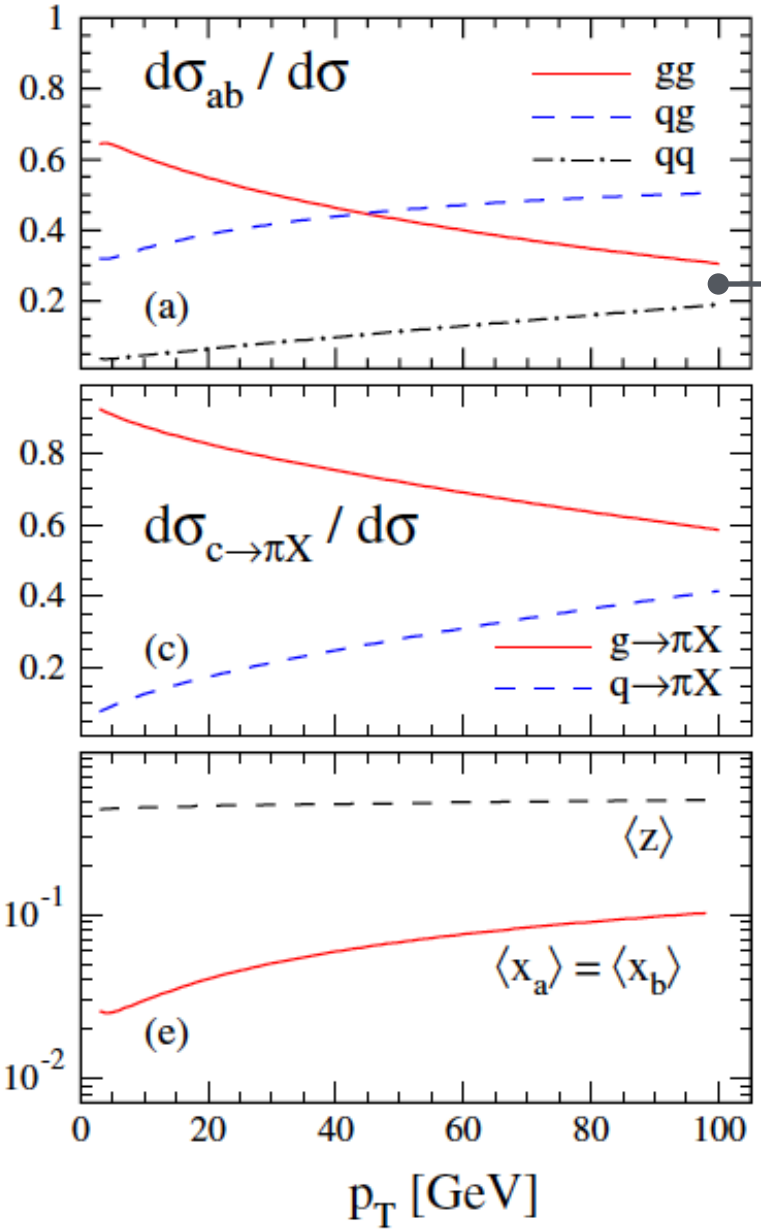
2 phenomenology of inclusive hadron production

R. Sassot, MS, P. Zurita, PRD82 (2010) 074011
D. de Florian, R. Sassot, M. Epele, R. Hernandez-Pinto, MS, PRD91 (2015) 014035
D. d' Enterria, K.J. Eskola, I, Helenius, H Paukkunen, NPB883 (2014) 615

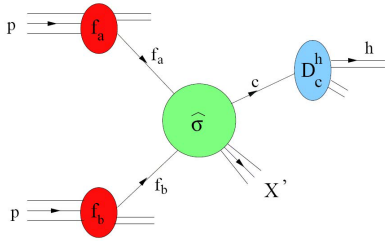
what PDFs/FFs do we probe and where?

R. Sassot, MS, P. Zurita, PRD82 (2010) 074011

for 7 TeV but *approx*. scales with $x_T = 2p_T / S^{1/2}$



π^0 production at mid rapidity



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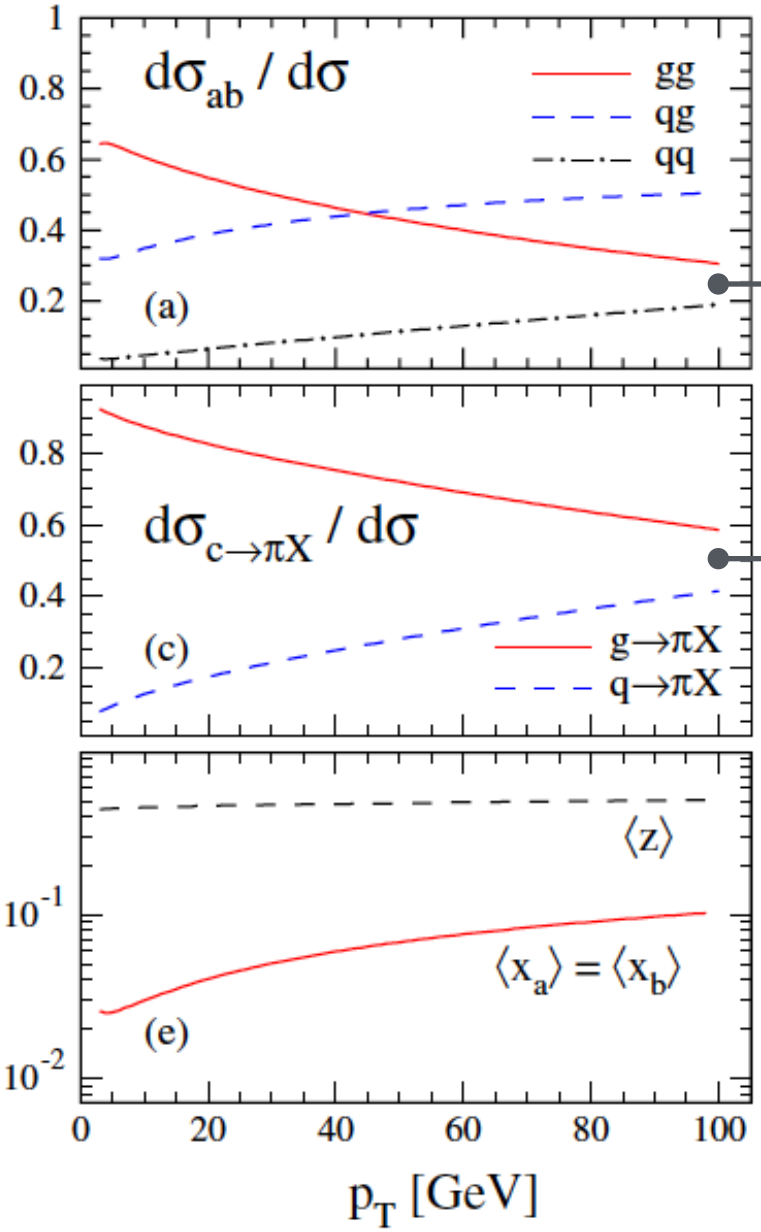

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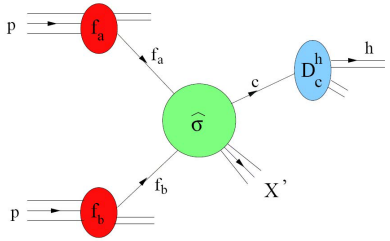

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majority of pions comes from gluon-to-pion FF

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R. Sassot, MS, P. Zurita, PRD82 (2010) 074011

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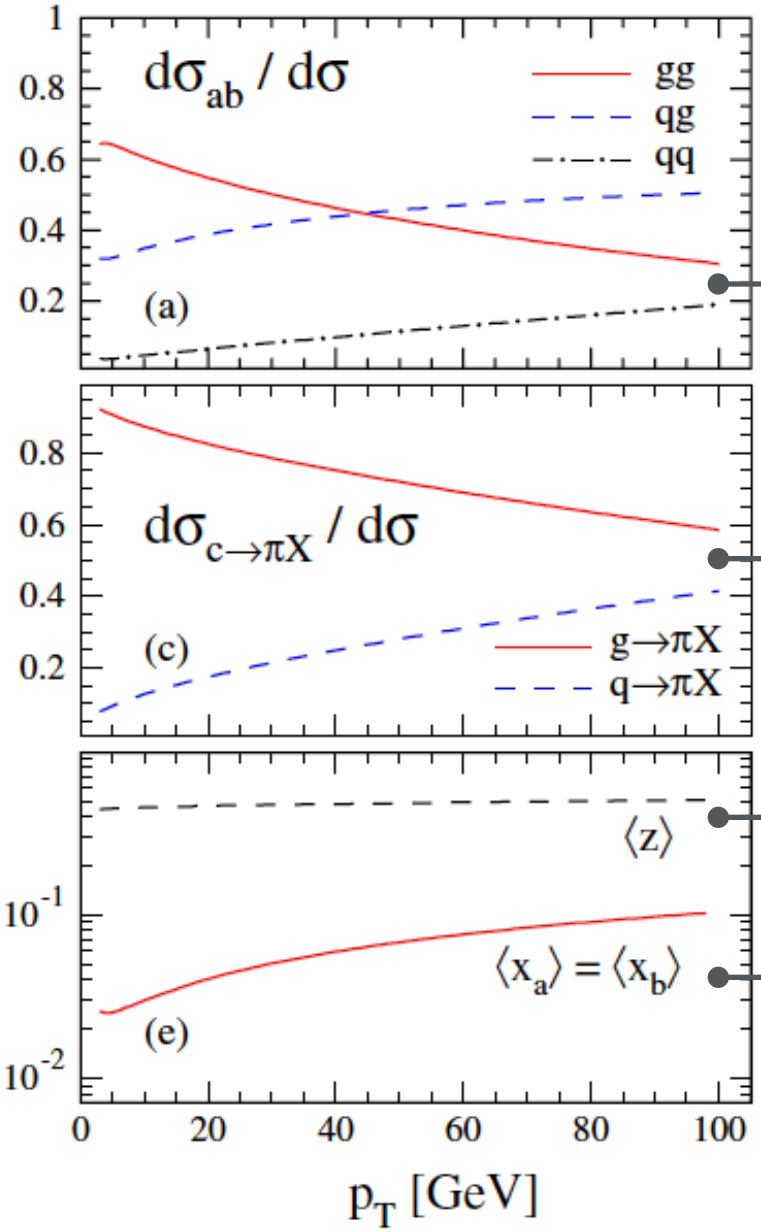
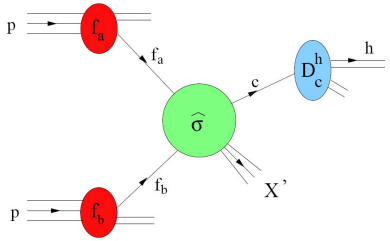


π^0 production at mid rapidity



dominated by gg and qg scattering

majority of pions comes from gluon-to-pion FF

most pions carry 40-50% of fragmenting parton's momentum

$$\langle z \rangle \equiv \frac{\int dz z \frac{d\sigma^H}{dz dp_T}}{\int dz \frac{d\sigma^H}{dz dp_T}}$$

PDFs are probed at medium x where they are well constrained

what PDFs/FFs do we probe and where?

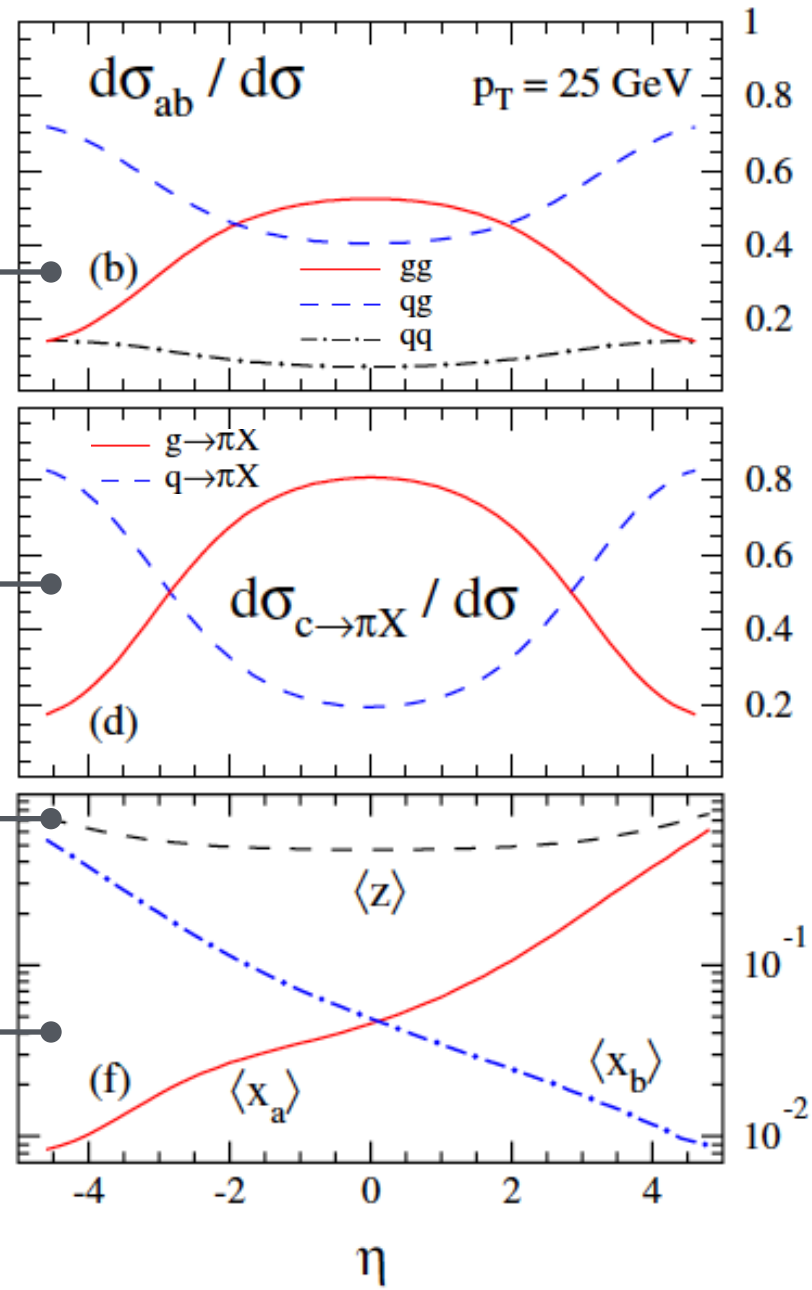
π^0 production vs. rapidity

mainly gluon-valence quark scattering at large rapidities

quark-to-pion FF dominant at large y

mean z of FFs increases with rapidity

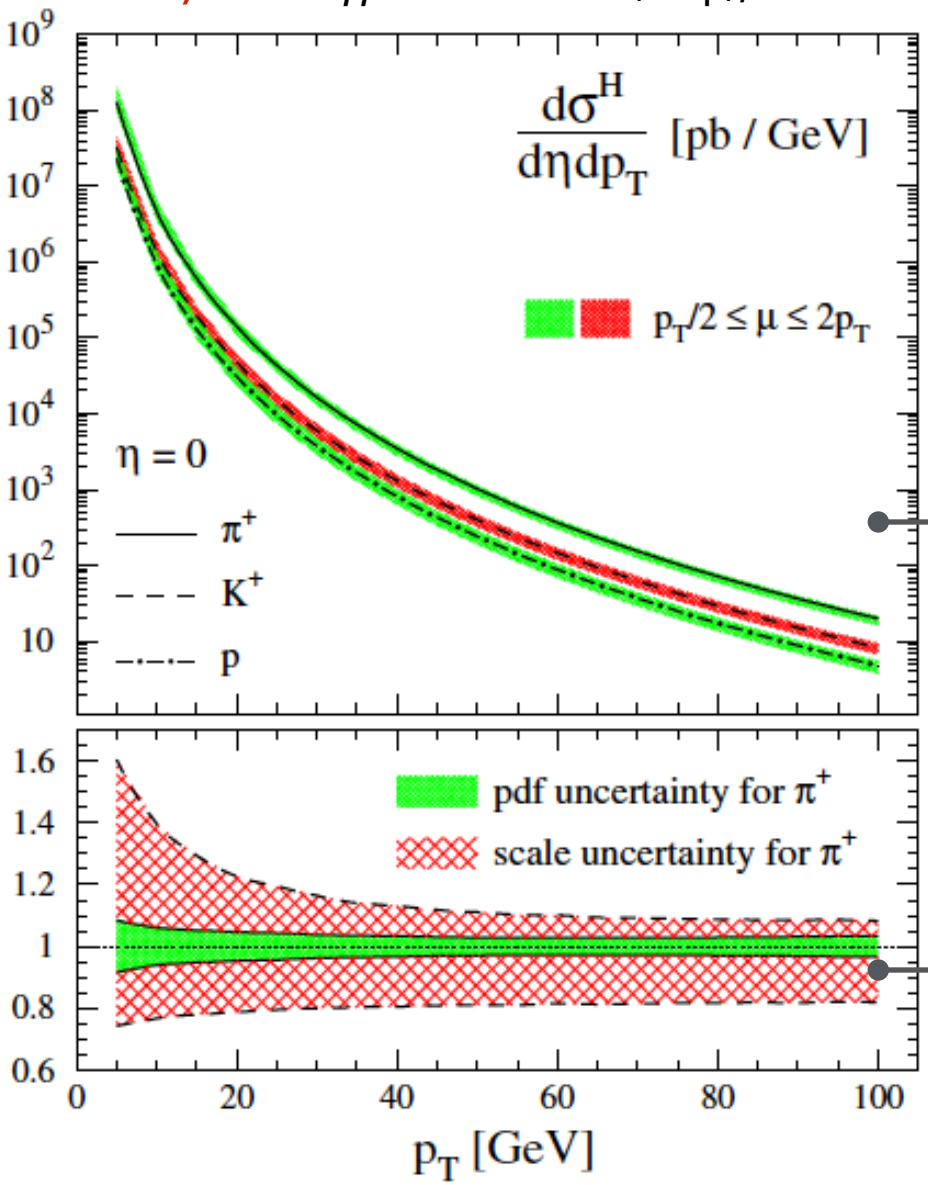
PDFs probed asymmetrically



applies to other hadron species as well

typical theoretical uncertainties

for 7 TeV but *approx*. scales with $x_T = 2p_T / S^{1/2}$



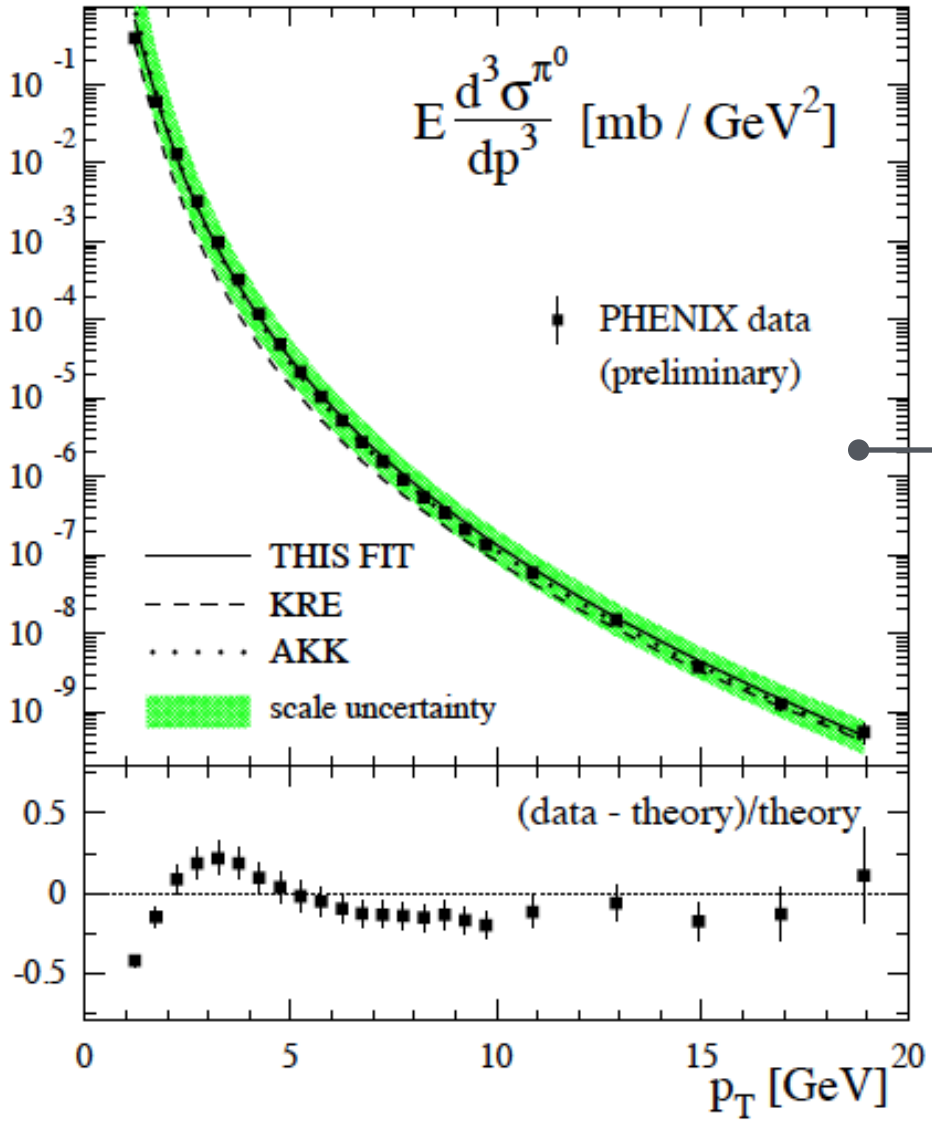
scale uncertainty for π, K, p production using DSS 07/08 FFs

scale uncertainty significantly larger than PDF uncertainties

—> need NNLO calculation to improve!

ALICE vs PHENIX data - some tension

DSS 07/08 (π, K): D. de Florian, R. Sassot, MS, PRD75 (2007) 114010



DSS set of FFs did a very good job in describing world data on pions (e^+e^-, ep, pp)

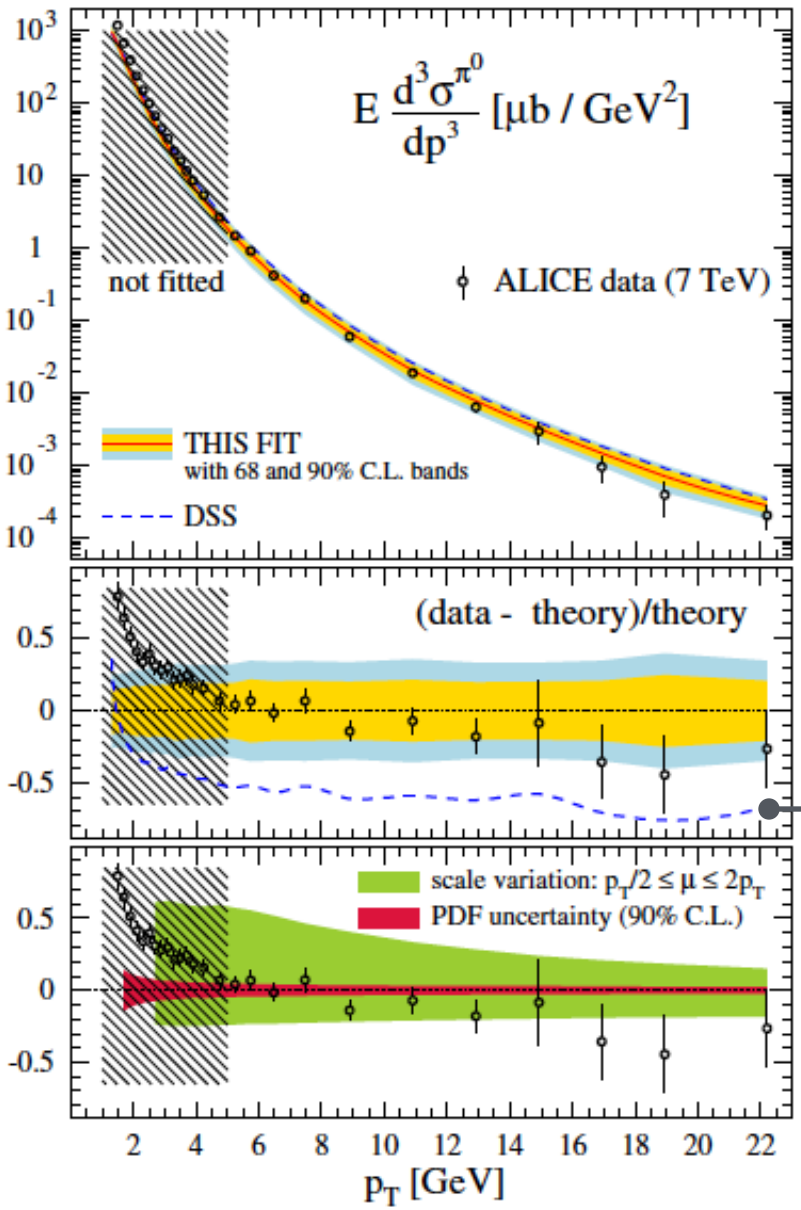
main pp input: PHENIX @ 200 GeV
NLO works down to unexpectedly (?) small p_T

achieved with larger gluon-to-pion FF
than in previous fits based only on e^+e^- data

... then ALICE came along ...

ALICE vs PHENIX cont'd

DSS 14: D. de Florian, R. Sassot, MS, PRD91 (2015) 014035

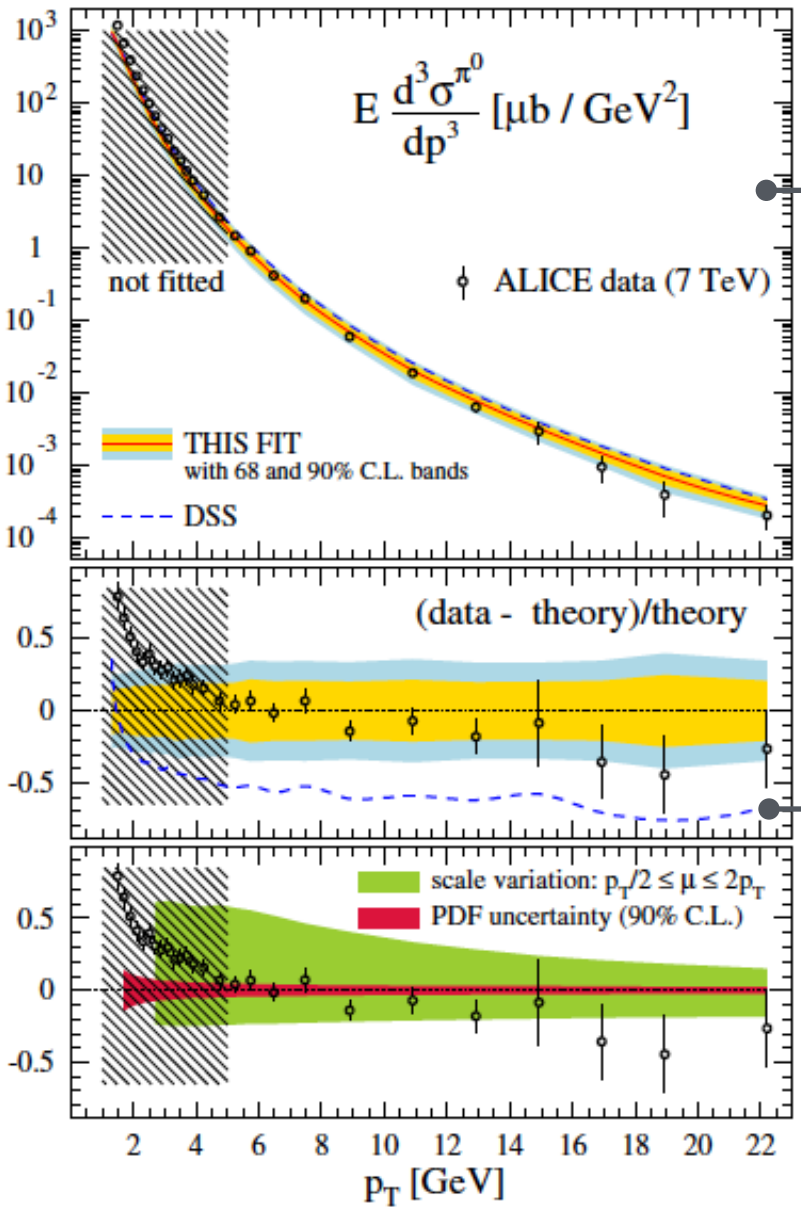


NLO with DSS 07/08 FFs grossly overshoots data

highly unusual: if something is missing in NLO one usually *undershoots* data

ALICE vs PHENIX cont'd

DSS 14: D. de Florian, R. Sassot, MS, PRD91 (2015) 014035



only way to accommodate 7 TeV ALICE data:

- leave out pp data below about p_T = 5 GeV
- reduce gluon-to-pion FF as much as possible (PHENIX!)

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ALICE vs PHENIX cont'd

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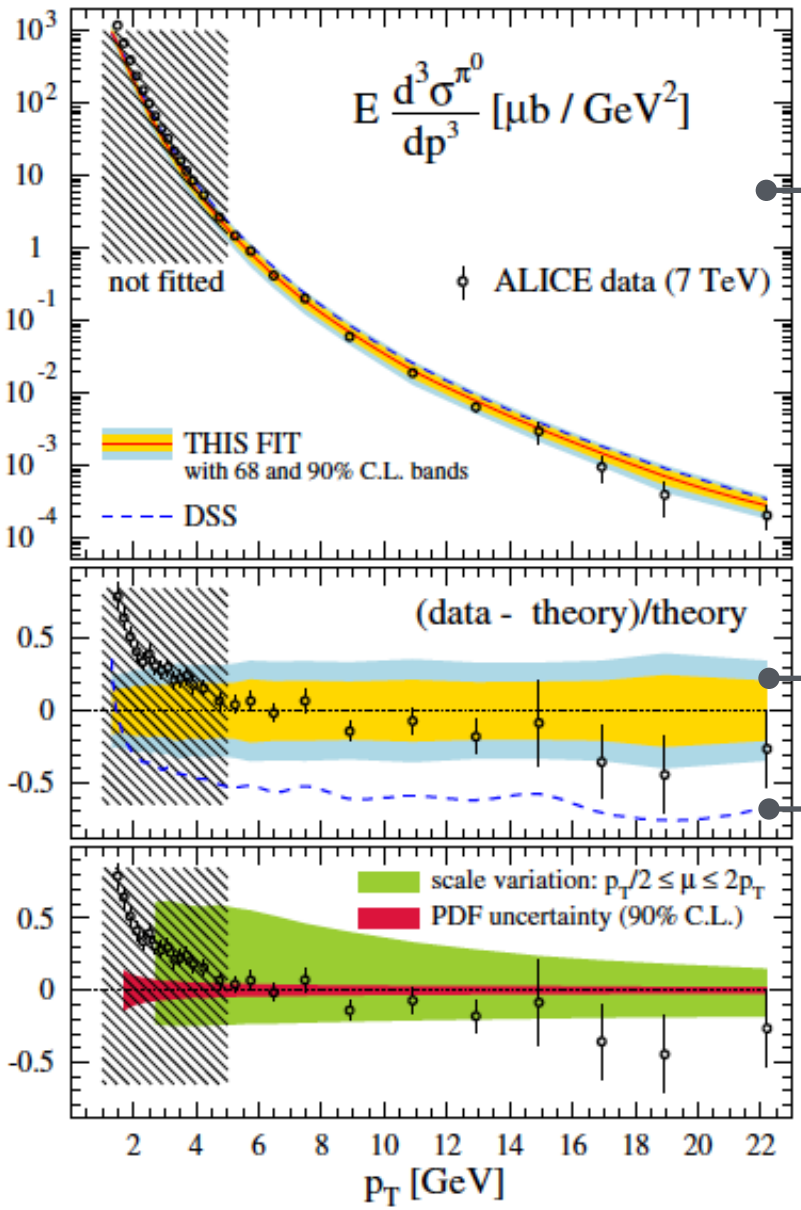

only way to accommodate 7 TeV ALICE data:

- leave out pp data below about p_T = 5 GeV
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led to new set of pion FFs: DSS '14

new asset: FF uncertainty sets

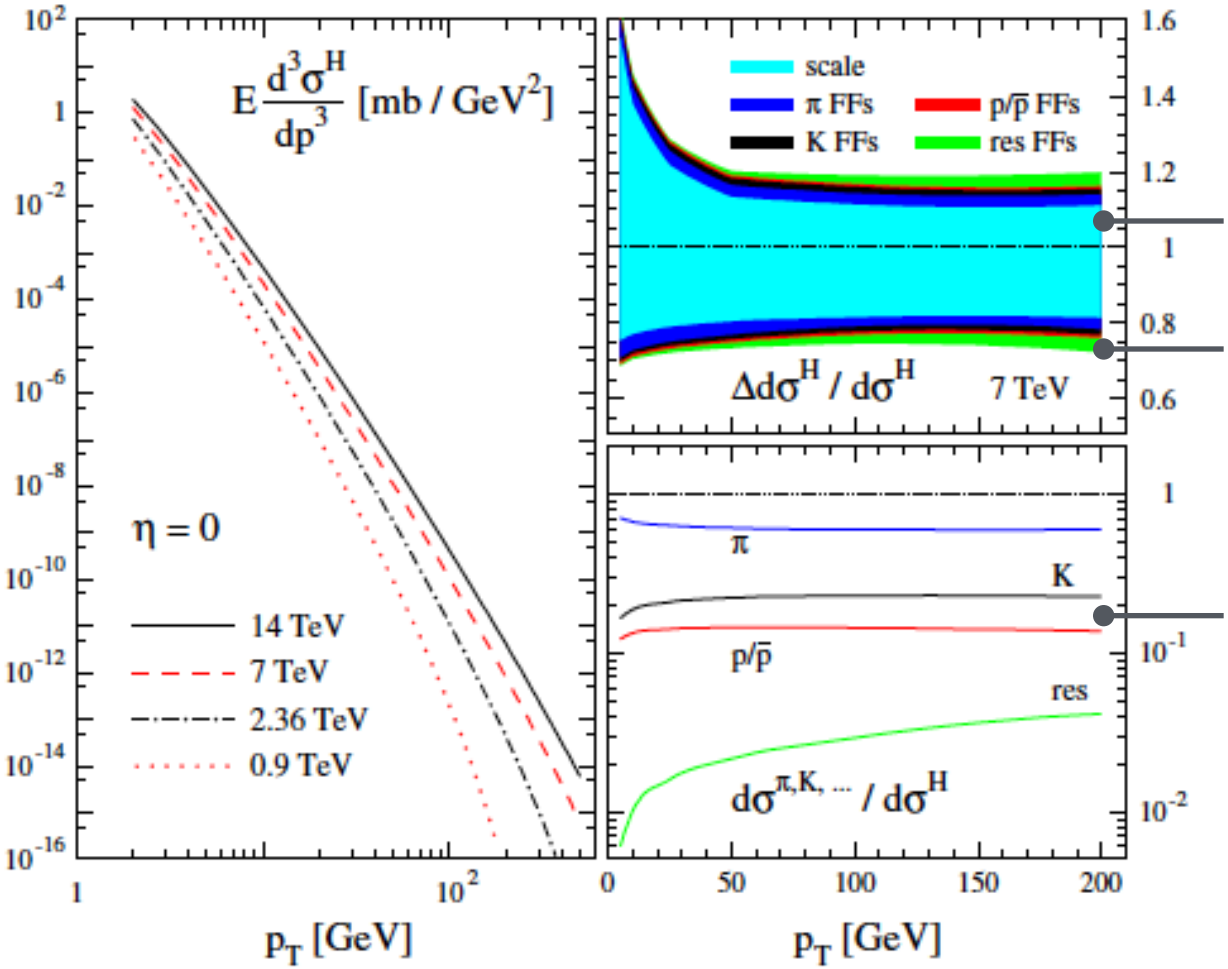
NLO with DSS 07/08 FFs grossly overshoots data

highly unusual: if something is missing in NLO one usually *undershoots* data

hadron "chemistry"

unidentified charged hadron spectra can be of interest as well (in particular, if you lack particle ID)

DSS 07/08 (p, H): D. de Florian, R. Sassot, MS, PRD76 (2007) 074033
R. Sassot, MS, P. Zurita, PRD82 (2010) 074011



scale uncertainty dominant

uncertainties on FFs

in DSS 07/08 @ 7 TeV:
pions: 60%
kaons: 22%
(anti)-protons: 13%

back then we had no LHC data ...

more trouble with LHC data

DSS determined unidentified hadron FFs through series of separate global fits:

- **pions, kaons, and protons from e^+e^-, ep, and pp data; sum them up and fit "residual" to H data**
- **important sanity check: "residual" positive and small** ✓

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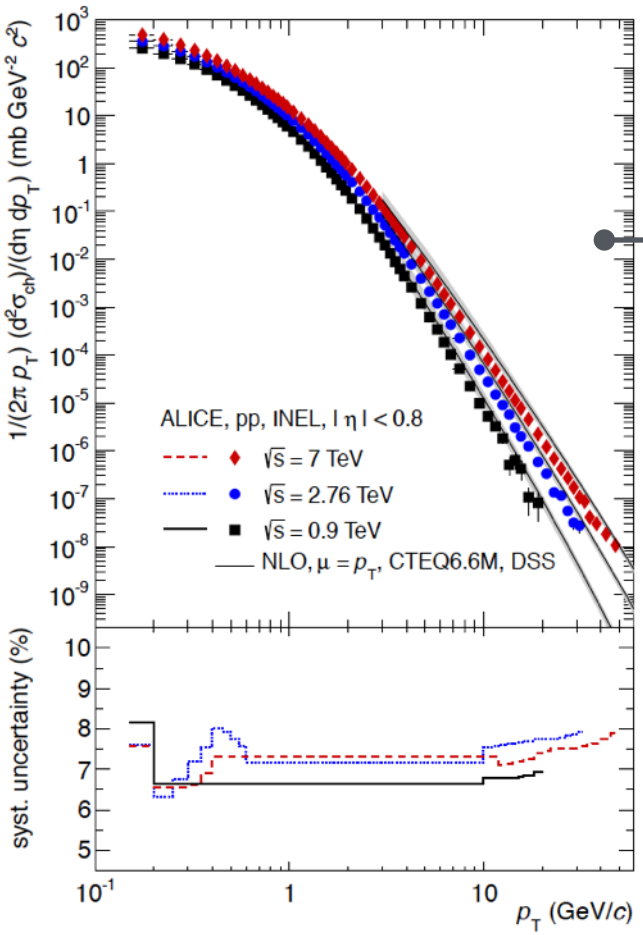
ALICE results on unidentified charged hadrons EPJ C73(2013)2662

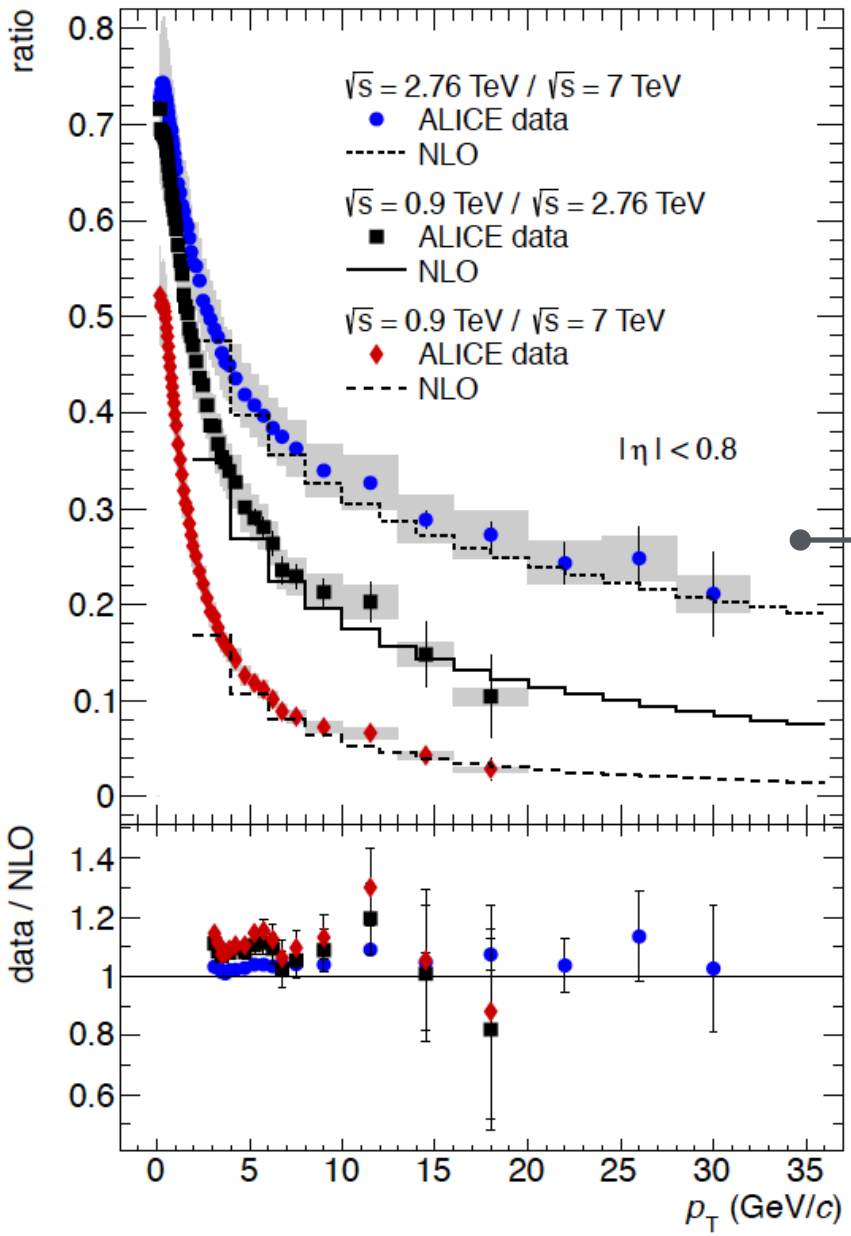


as expected from pion result:
DSS 07/08 overshoots hadron yields

no reanalysis available yet - work in progress
(awaiting new SIDIS kaon results)

just arrived 2 days ago, looks promising!

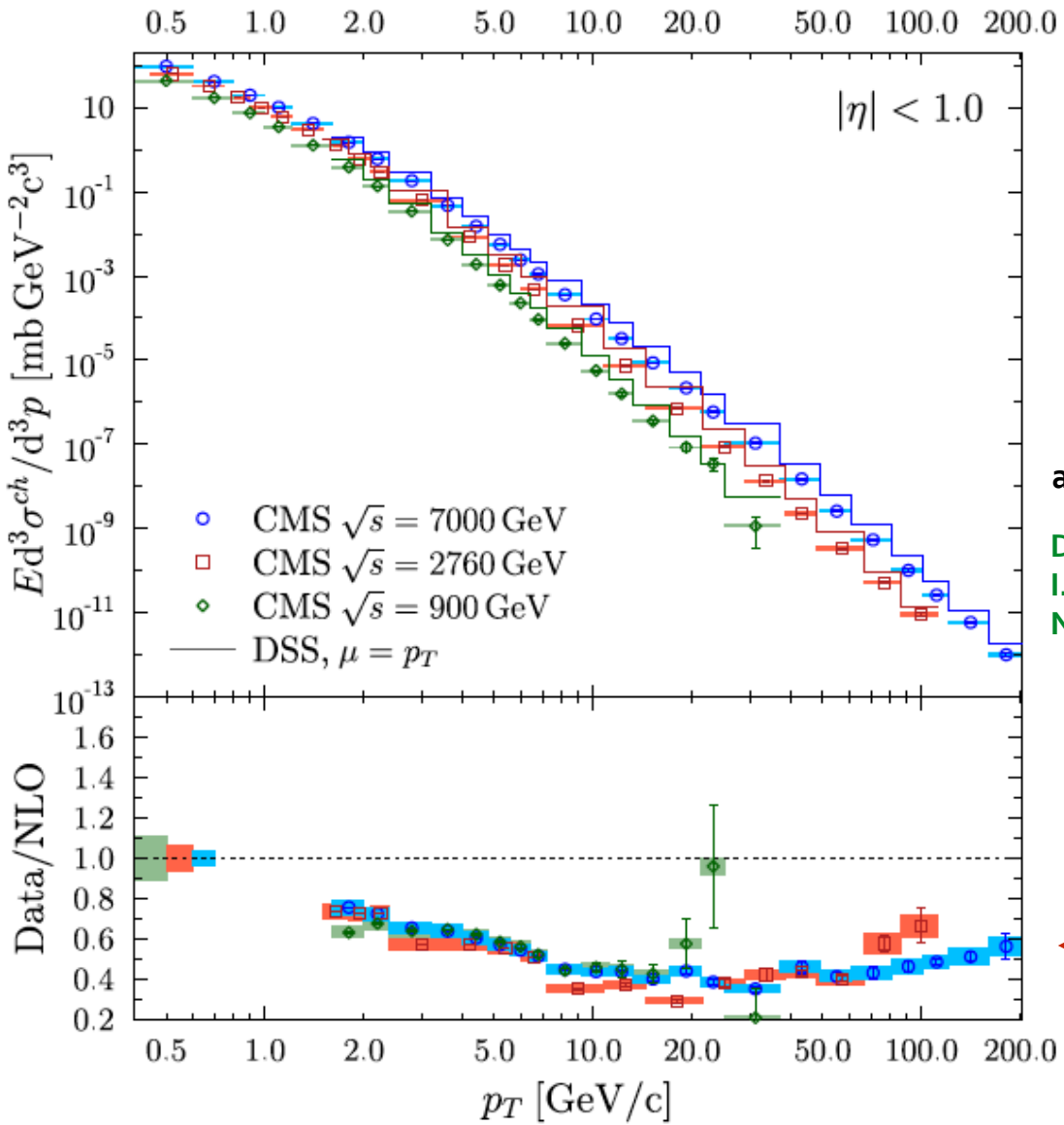
unidentified hadrons cont'd



the good news:
NLO gets the energy dependence right

unidentified hadrons cont'd

similar "problems" with CMS data JHEP 1108 (2011) 086, EPJ C72(2012)1945



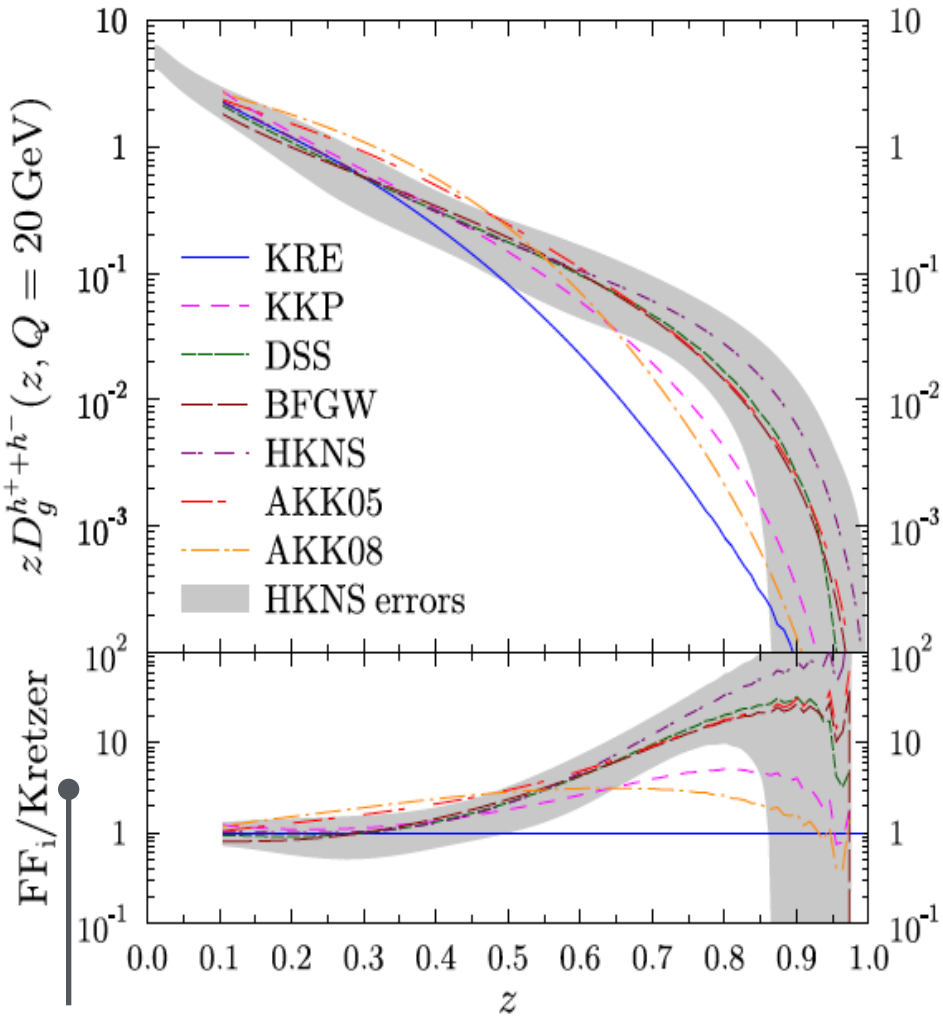
as noticed in

D. d' Enterria, K.J. Eskola, I. Helenius, H. Paukkunen, NPB883(2014)615

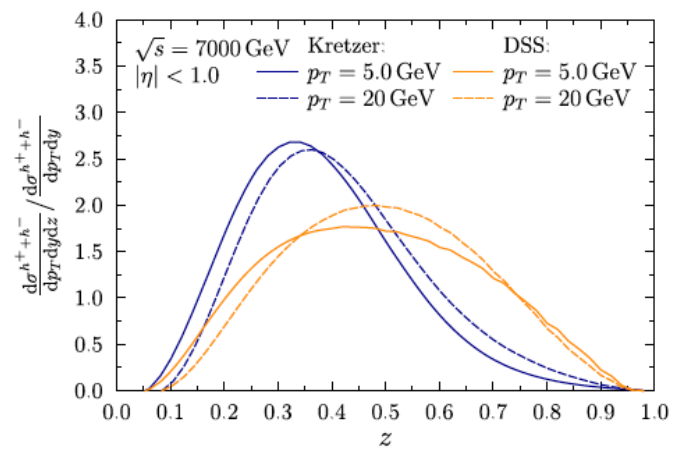
unidentified hadrons cont'd

as for pions a much softer gluon FF helps to reconcile data (needs new global fit to confirm)

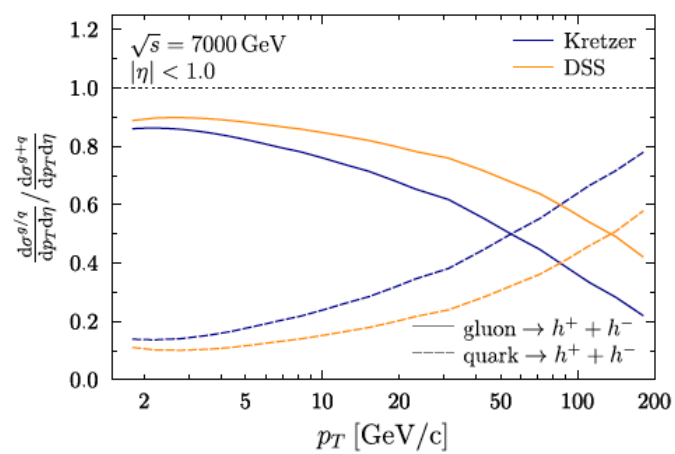
exploratory study in D. d' Enterria et al., NPB883(2014)615



redistributes NLO cross section towards smaller z as favored by LHC data



more hadrons arise from quarks than gluons



"Kretzer": old FF set based on e^+e^- data with the smallest gluon FF

unidentified hadrons cont'd

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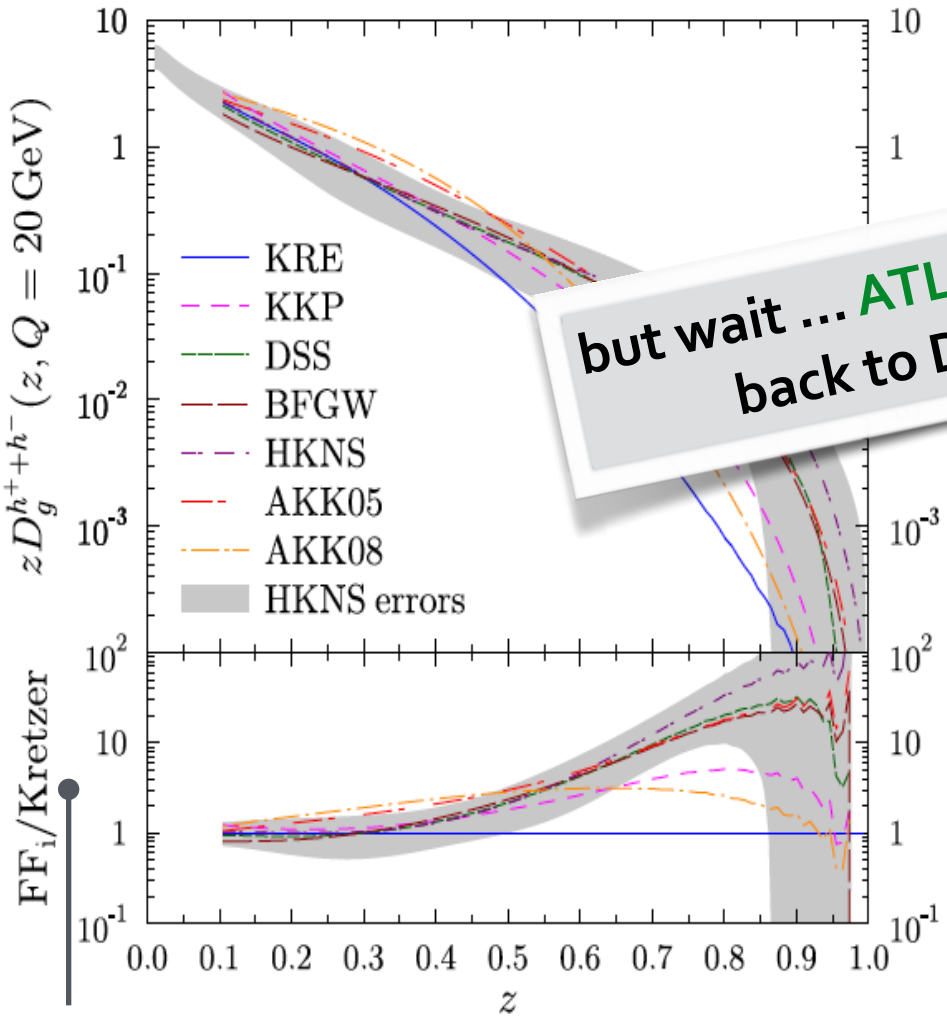

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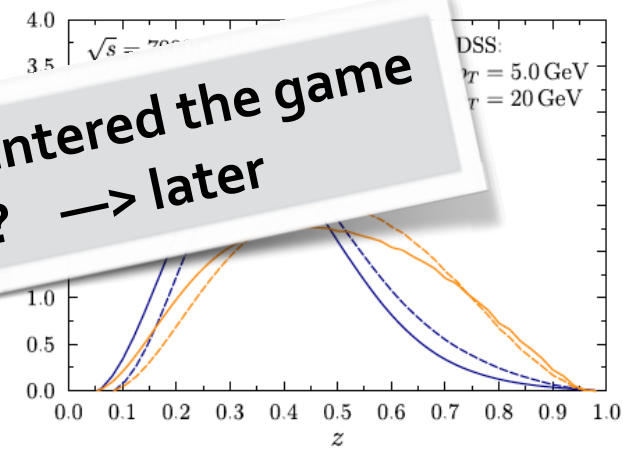
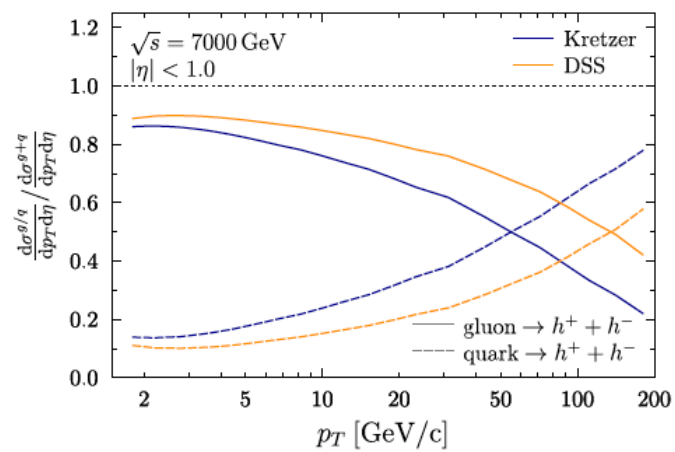


but wait ... ATLAS just entered the game
back to DSS '07 ?? —> later

more hadrons arise from quarks than gluons



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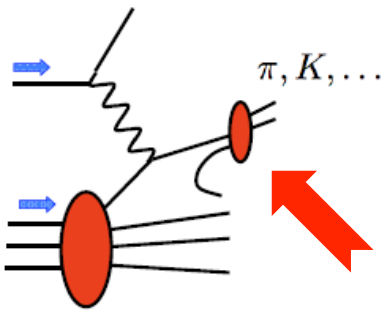
3

fragmentation functions
a very quick tour/overview

D. de Florian, R. Sassot, MS, PRD 75 (2007) 114010; 76 (2007) 074033
D. de Florian, R. Sassot, M. Epele, R. Hernandez-Pinto, MS, PRD91 (2015) 014035

definition, basics, limitations



crucial for pQCD interpretation (factorization)
of all data with detected (identified) hadrons, e.g.,
SIDIS HERMES, COMPASS, pp —>πX PHENIX, ALICE, CMS, ...

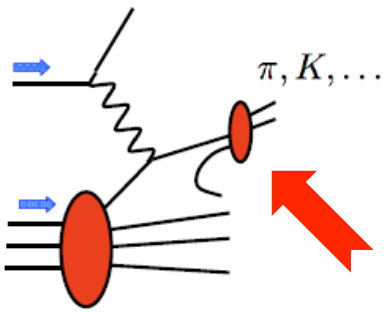
- formal definition:

  Collins, Soper '81, '83

$$D(z) \simeq \int dy^- e^{iP^+/zy^-} \mathrm{Tr}\gamma^+ \langle 0| \psi(y^-) |hX\rangle \langle hX| \overline{\psi}(0) |0\rangle$$

no inclusive final-state
no local OPE --> no lattice formulation

definition, basics, limitations



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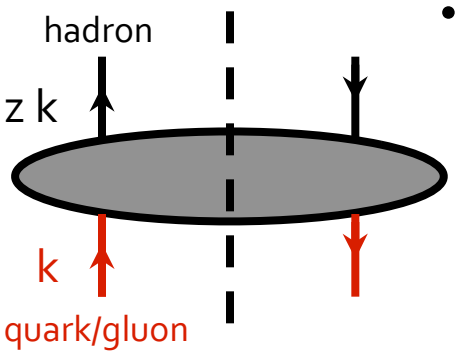
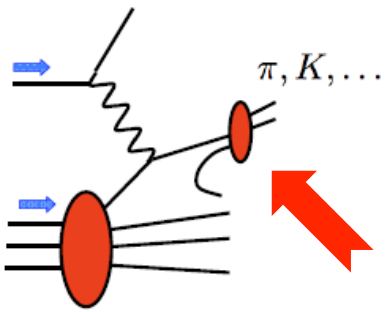


- basics:
  - describe the *collinear* transition of a *massless* parton "i" into a *massless* hadron "h" carrying fractional momentum z
  - fragmentation assumed to be independent of other colored particles
  - inclusive quantities - do *not* describe leading hadrons
  - sum rule $\sum_h \int_0^1 z D_i^h(z,\mu) = 1$ a parton i fragments with 100% probability into "something" preserving its momentum

definition, basics, limitations



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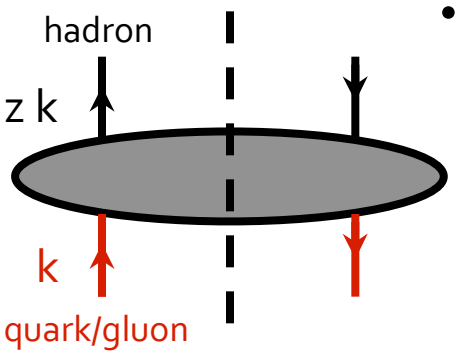

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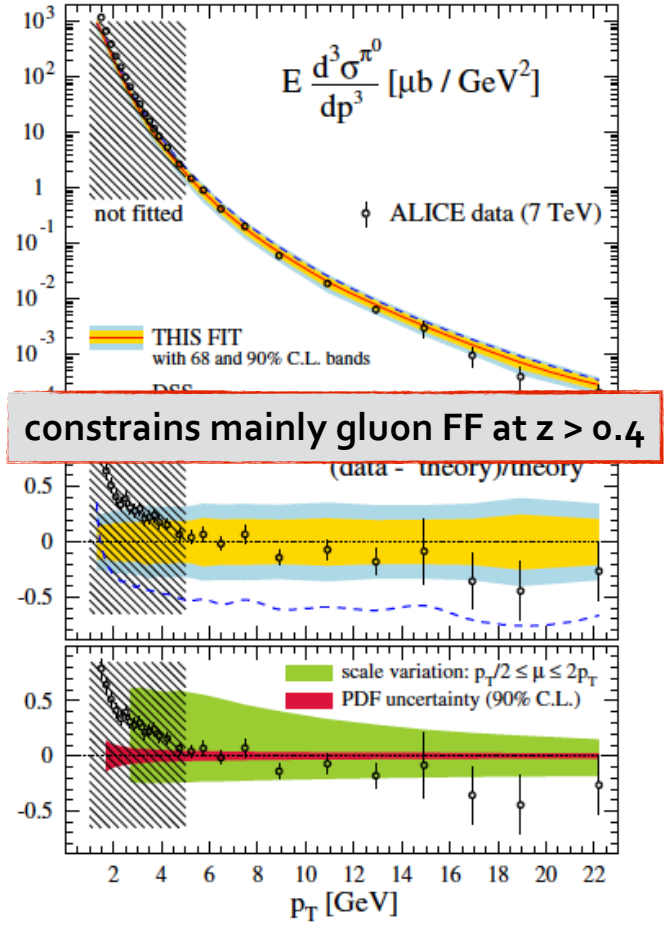
- limitations:
  - ☑ large enough z (typically z > 0.05 or 0.1 to avoid finite mass effects, …)
  - ☑ processes characterized by hard scale (to ensure factorization)

modern FFs: synergy of different probes

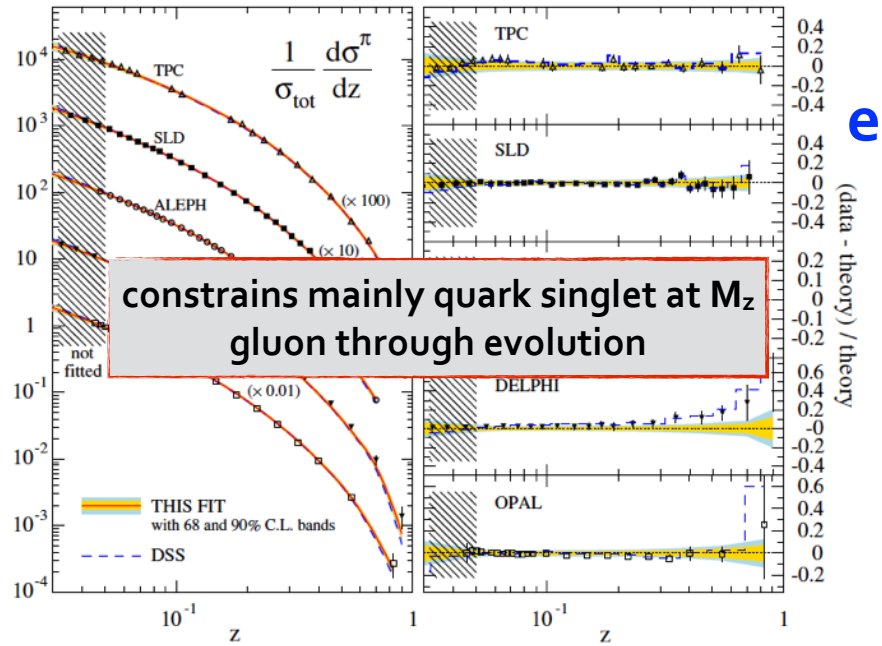
- different probes constrain different aspects of FFs: flavor, z range, scale
- verify universality/factorization

pp



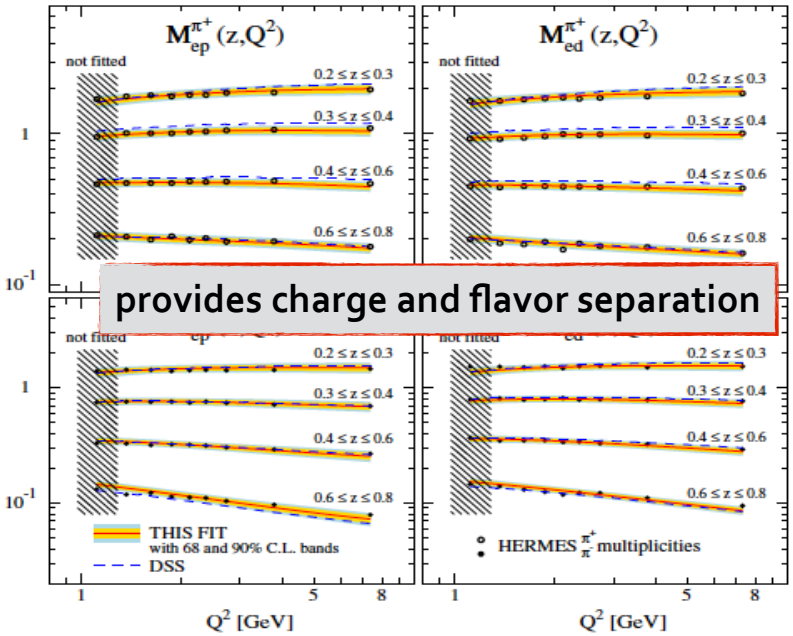
constrains mainly gluon FF at z > 0.4

e^+e^-



constrains mainly quark singlet at M_Z
gluon through evolution

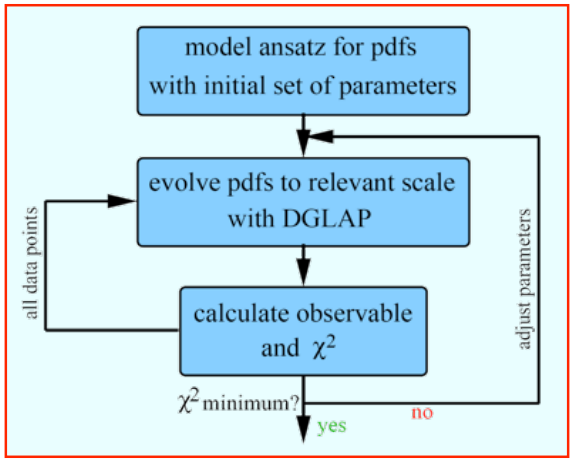
ep



provides charge and flavor separation

anatomy of a global QCD analysis

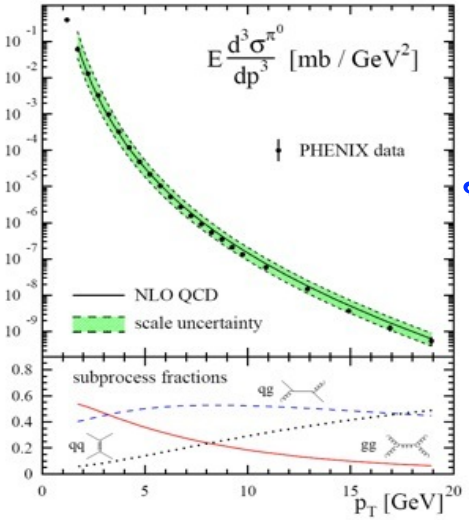
obtain FFs
through global χ^2 optimization



set of **optimum parameters**
for *assumed* functional form

analysis of uncertainties

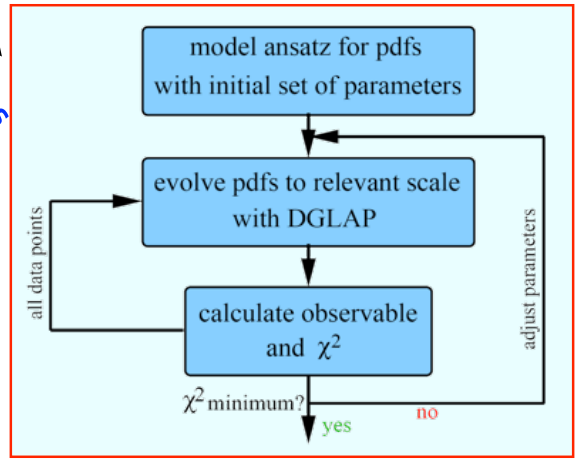
anatomy of a global QCD analysis



pp only up to NLO: Aversa et al.; Jager et al.; ...
resummations to estimate NNLO

hard cross sections
all-order resummations

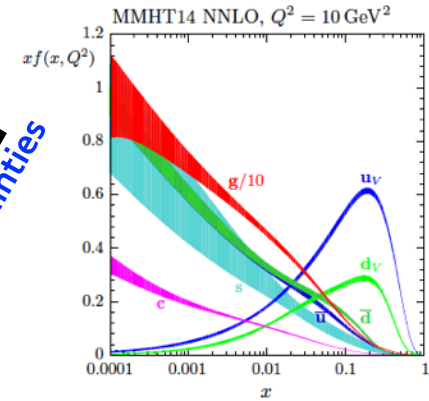
obtain FFs
through global χ^2 optimization



set of **optimum parameters**
for *assumed* functional form

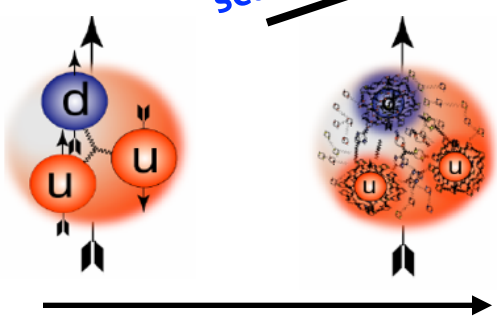
analysis of uncertainties

non-pert. inputs
PDFs & uncertainties



MMHT, CTEQ, NNPDF, ...

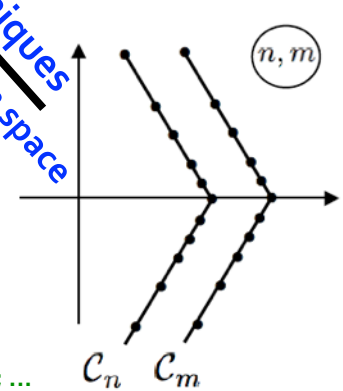
scale evolution kernels



"resolution scale" μ

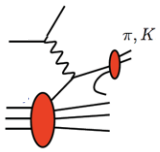
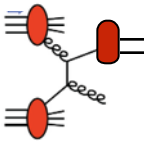
up to NNLO: Almasy, Moch, Vogt

novel techniques
e.g. in complex Mellin space

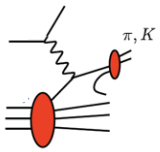
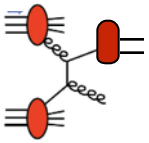


Vogt et al.;
MS, Vogelsang; ...

what's on the market: recent NLO fits

acronym	hadron species				uncertainties	LHC data
DSS 07/08 de Florian, Sassot, MS	$\pi^{\pm}, K^{\pm}, p, H^{\pm}$	✓	✓	✓	✓	✗
DSS 14 de Florian, Sassot, MS, Epele, Hernandez-Pinto	$\pi^{\pm}$	✓	✓	✓	✓	✓

what's on the market: recent NLO fits

acronym	hadron species				uncertainties	LHC data
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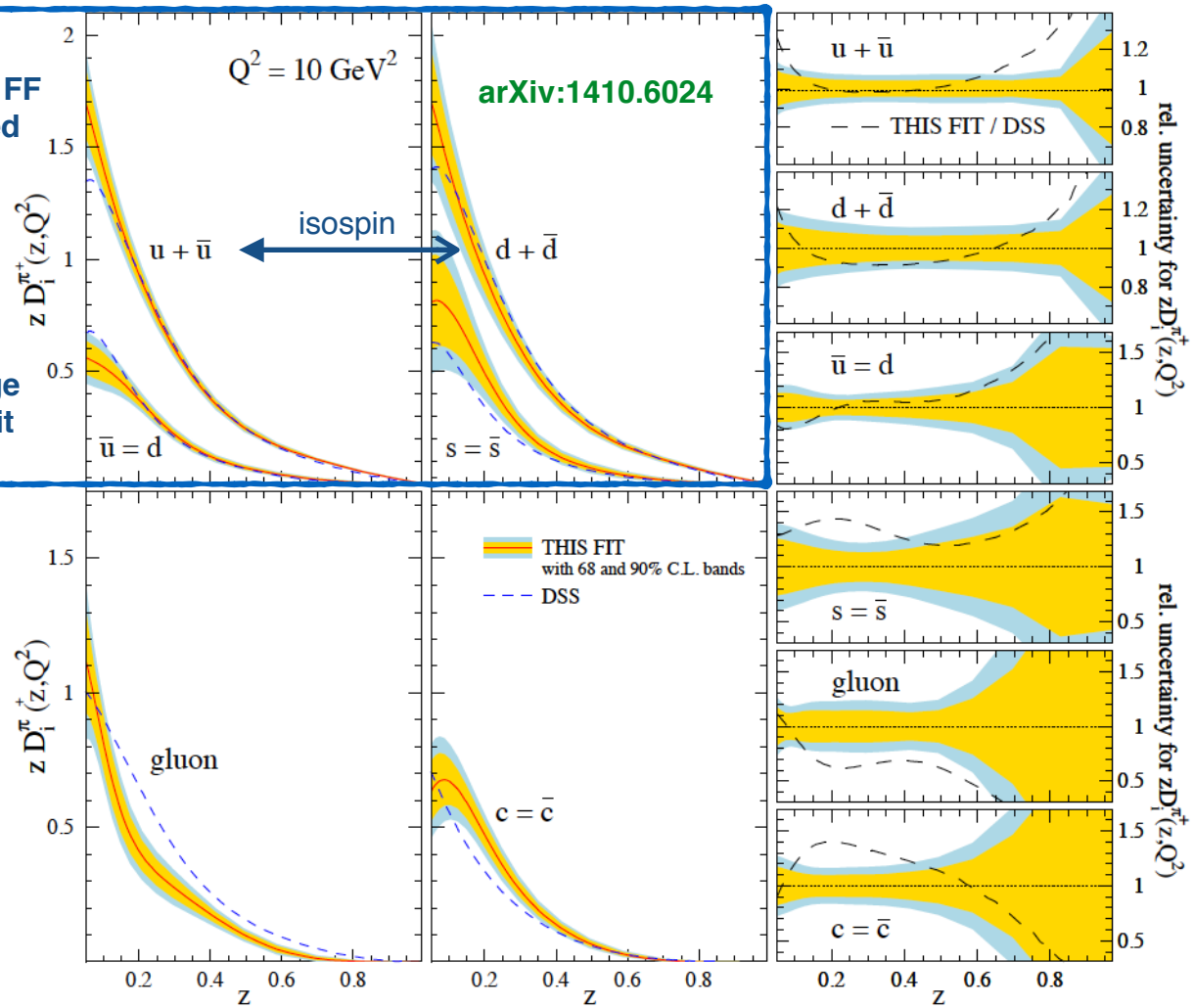
AKK 08 Albino, Kniehl, Kramer	$\pi^\pm, K^\pm, p$	✓	✗	✓	✗	✗
HKNS Hirai et al.	$\pi^\pm, K^\pm, p$	✓	✗	✗	✓	✗
BFGW Bourhis et al.	$H^\pm$	✓	✗	✗	✓	✗
Kretzer S. Kretzer	$\pi^\pm, K^\pm, H^\pm$	✓	✗	✗	✗	✗
AESSS Aidala, Ellinghaus, Seele, Sassot, MS	η	✓	✗	✓	✗	✗
DSV de Florian, MS, Vogelsang	Λ	✓	✗	✗	✗	✗

meet the DSS '14 pion FFs & their uncertainties

main features:
- ☑ new data allow for first reliable uncertainty estimate of FFs (with Hessian method)
- ☑ excellent global description of all sets [biggest "tension" among RHIC & LHC pp data]

light quark -> pion FF largely unchanged

u/d isospin/charge symmetry from fit



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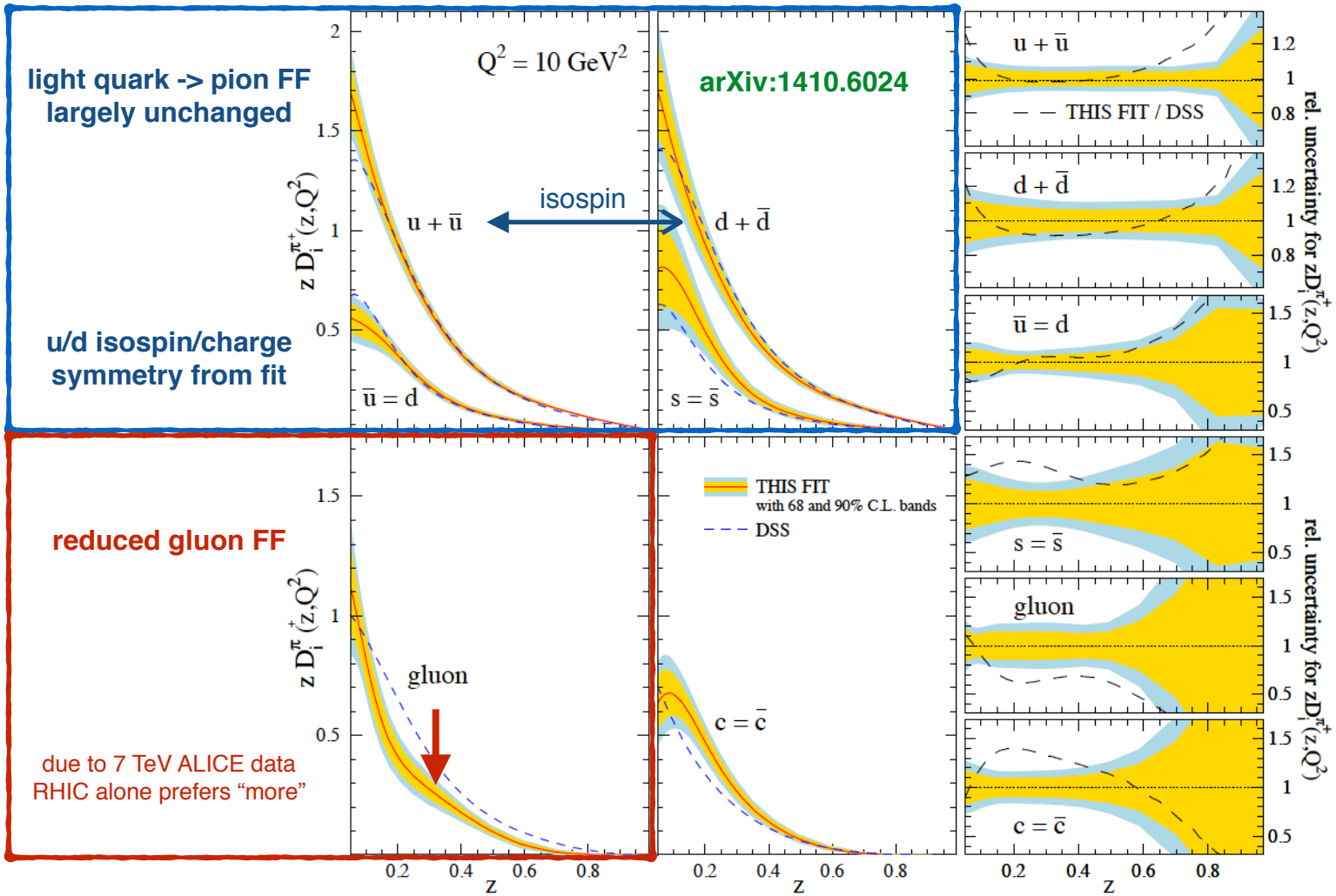
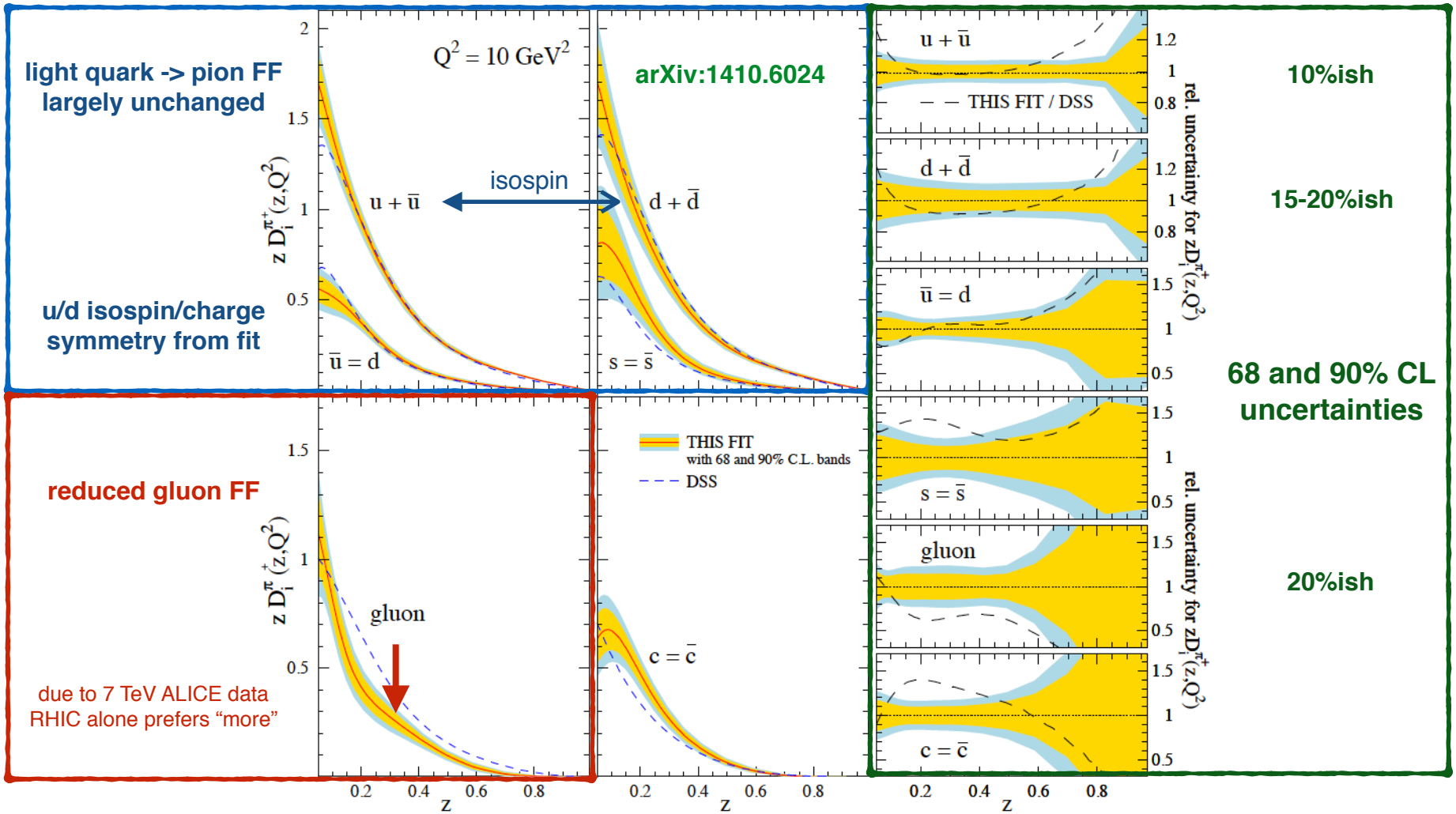


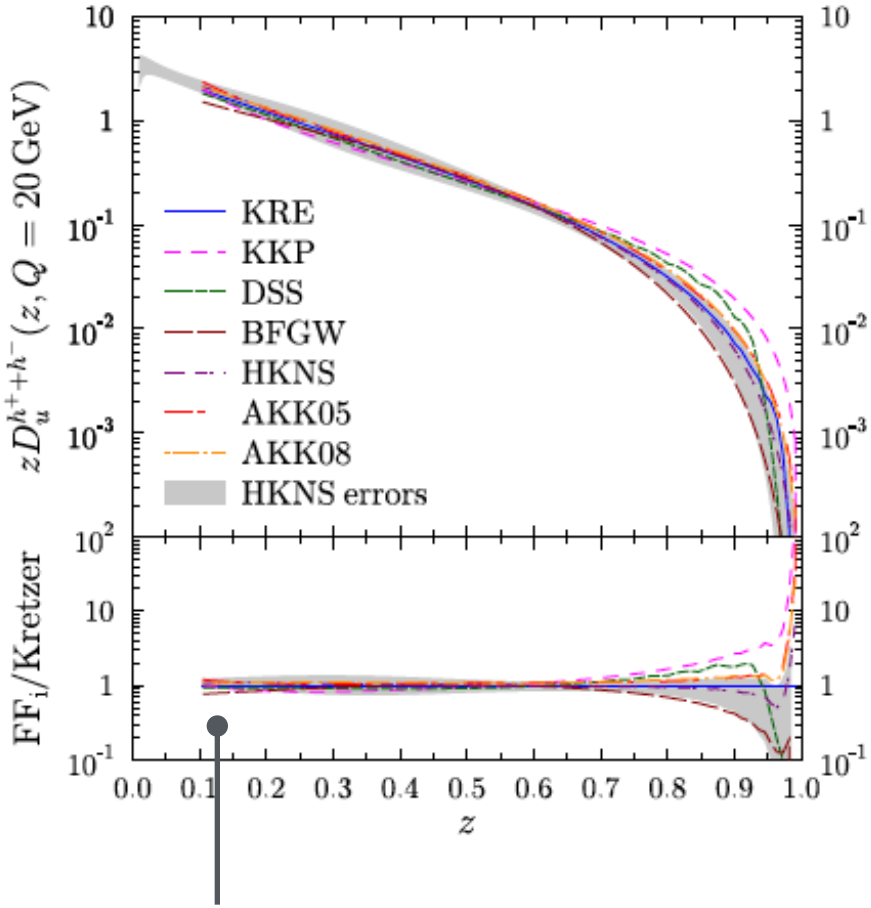
meet the DSS '14 pion FFs & their uncertainties

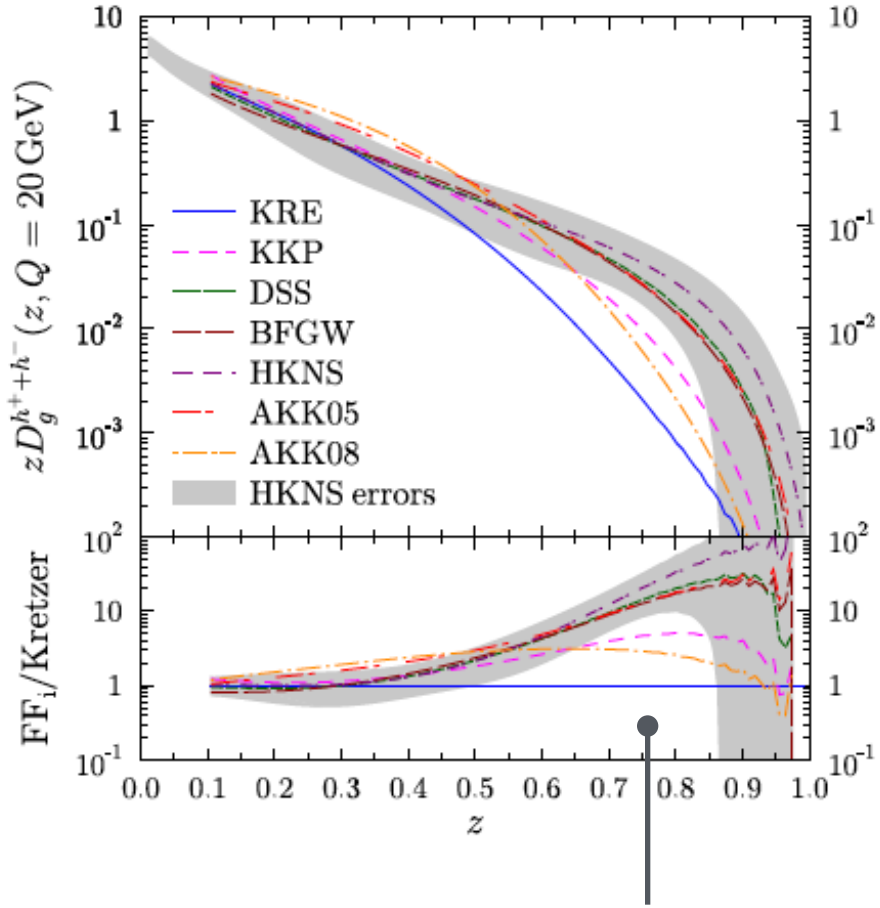
main features:
- ☑ new data allow for first reliable uncertainty estimate of FFs (with Hessian method)
- ☑ excellent global description of all sets [biggest "tension" among RHIC & LHC pp data]



comparison of charged hadron FFs

compilation from D. d' Enterria et al., NPB883(2014)615





good agreement for quark FF
mainly constrained by e^+e^- data used in all fits

large deviations at large z relevant for pp data
only DSS fitted pp data (UA1, UA2, CDF)
LHC data seems to prefer smaller Kretzer-like gluon

to-do list on FFs

- **LHC data have big impact on gluon FF**
  - need to update global analyses for kaons, proton, charged hadrons, …, eta, …
- **need to understand better the source of tension between RHIC & LHC data**
  - worst at low p_T (led to p_T cut in DSS 14 pion FF analysis)
    - **other production mechanisms** at work at low p_T beyond leading twist ?
  - all experiments incl. e^+e^- treat **secondary (feed-down) pions** (weak decays) differently
    - need to figure out if this is relevant / a big effect and where in z, p_T
- **another major uncertainty is s-to-kaon vs. u-to-kaon FF**
  - so far only constrained by low-energy SIDIS data with identified kaons
  - extremely relevant for proton spin puzzle, big impact on Δs helicity PDF extraction from SIDIS data
    - need new probes; difficult at the LHC (gluon dominance) but worth checking
- **push precision to NNLO to reduce theoretical uncertainties**
  - efforts have started, so far limited to e^+e^- D. Anderle, F. Ringer, MS

4 attempts to describe pA data

R. Sassot, MS, P. Zurita, PRD82 (2010) 074011
R. Sassot, MS, P. Zurita, PRD81 (2010) 054001
D. de Florian, R. Sassot, MS, P. Zurita PRD85 (2012) 074028

hadron production in pA collisions

Q: how far can one push the pQCD framework based on collinear factorization

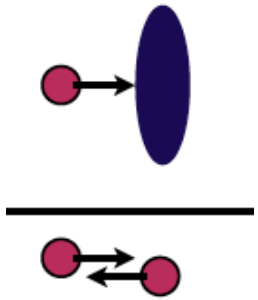
Q: how does hadronization proceed in a nuclear environment

☑ increasing amount of data available to address these questions

- semi-inclusive DIS off nuclear targets (HERMES)
- p/d A data from RHIC (BRAHMS, PHENIX, STAR)
- pPb data from the LHC (ALICE, ATLAS, CMS)

☑ exp. results for nuclear modification ratios amenable to pQCD *if* p_T is large

$$R^H_{p(d)A} =$$

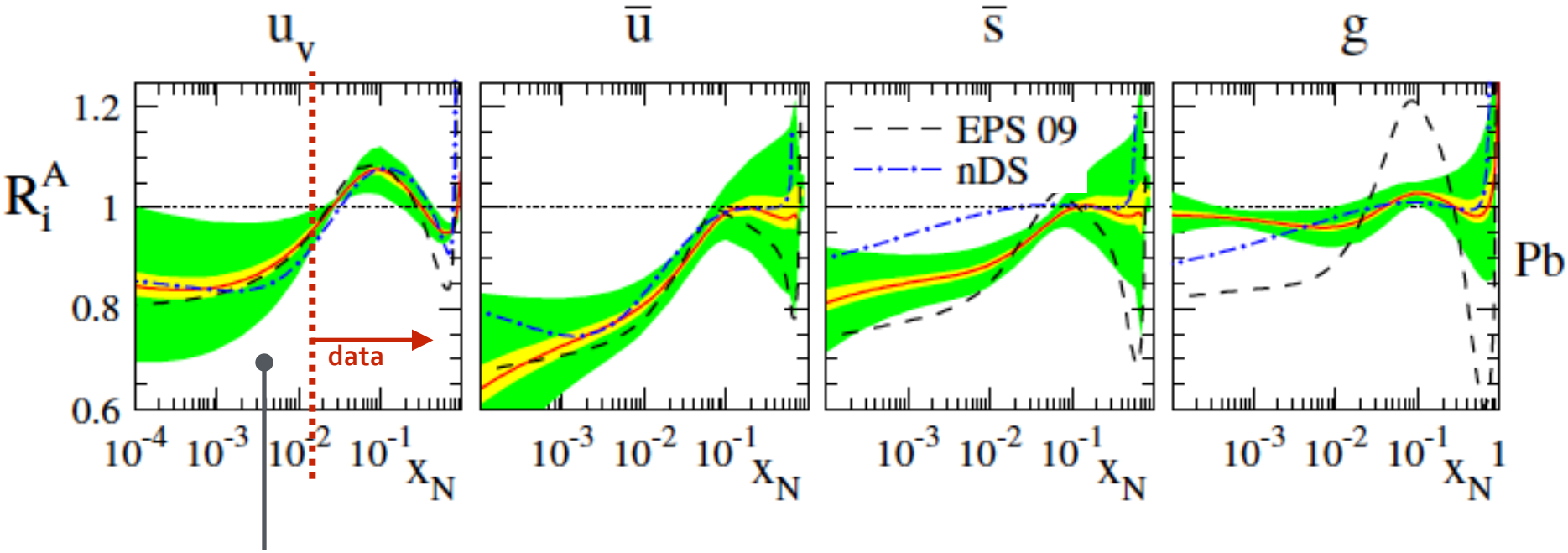


- same hard scattering and scale evolution eqs. for pA and pp
- use nuclear PDFs for pA calculation (the only knob in the calculation)
- same vacuum FFs everywhere

status of nPDFs

plot taken from D. de Florian, R. Sassot, MS, P. Zurita, PRD85(2012) 074028

- nPDFs only roughly constrained down to x=0.01 by fixed target eA DIS and pA DY data
- few NLO fits available: EPS 09, DSSZ, nCTEQ — EPS 09 and DSSZ include some RHIC dA data



observe textbook pattern
of "shadowing", "anti-shadowing",
"EMC effect", and "Fermi motion"

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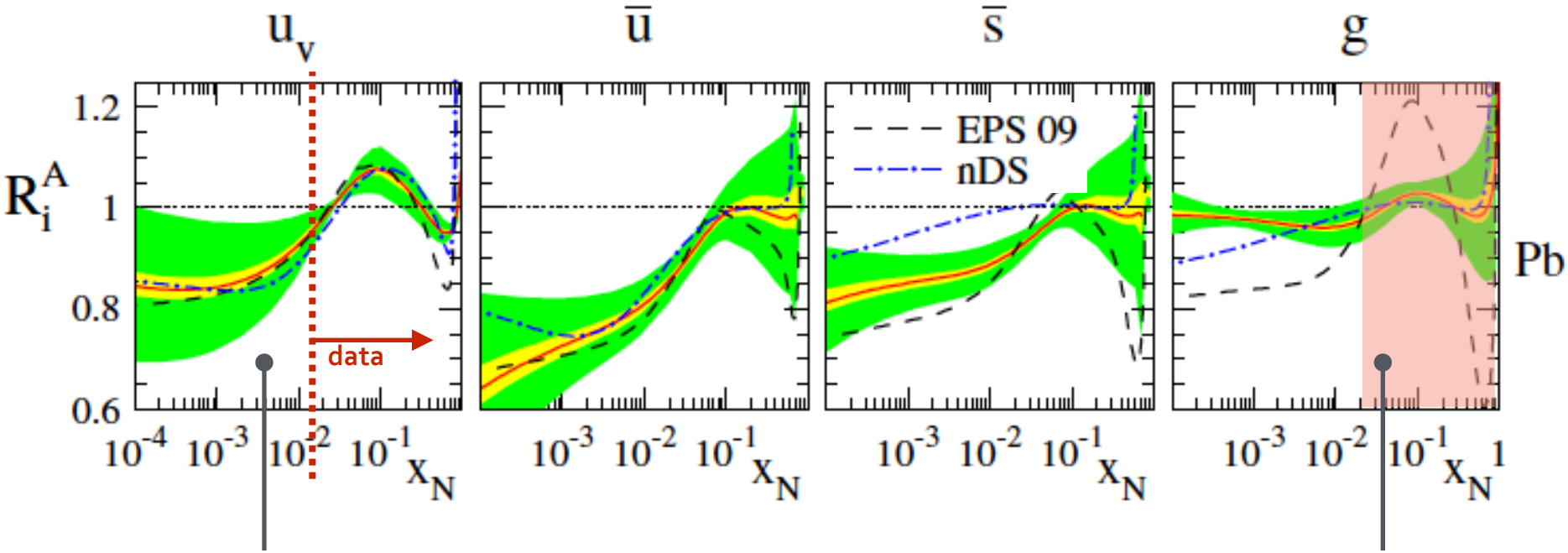

observe textbook pattern of "shadowing", "anti-shadowing", "EMC effect", and "Fermi motion"

pronounced differences between EPS 09 and DSSZ gluon modification
this will drive behavior of R_{pA}

additional input from RHIC & LHC pA data desperately needed

enhancement and/or suppression ?

$$d\sigma^{A}_{dA\to\pi X} = \sum_{ijk} f_i^d \otimes f_j^A \otimes d\hat{\sigma}_{ij\to kX} \otimes D_k^{A,\pi}$$

free proton PDF
"known"

nPDF
the only knob

known to NLO
[plus certain all-order resummations]
many contributing subprocesses

vacuum FFs
rather well known for pions
but what about possible final-state modifications?
can have an impact even if small

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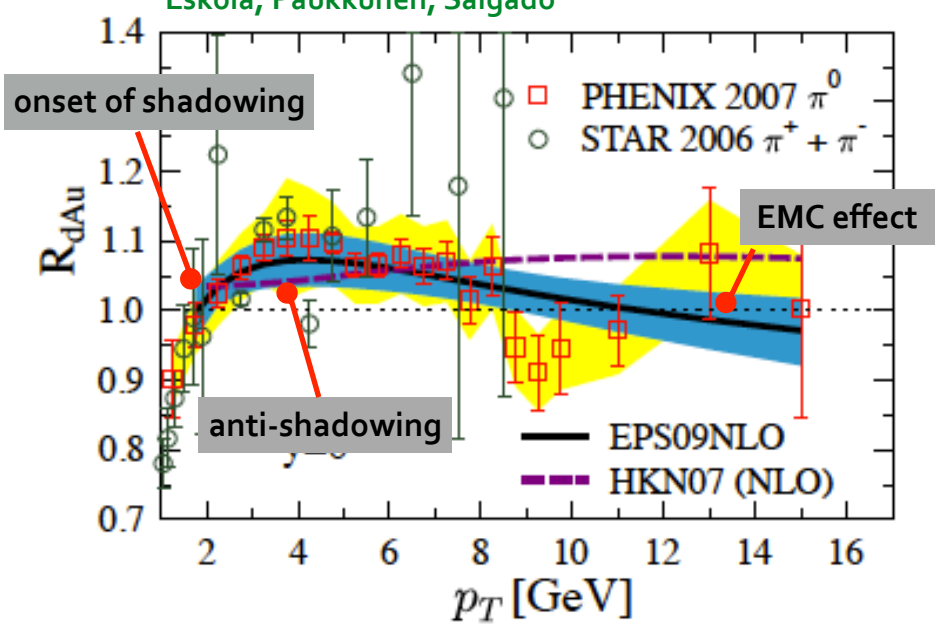
example: mid-rapidity neutral pion data from **PHENIX** and **STAR**

Eskola, Paukkunen, Salgado



- **first analyzed in EPS 09 fit**
- **R_{dAu} follows R_g modification**
- **explains strong modification of gluon**

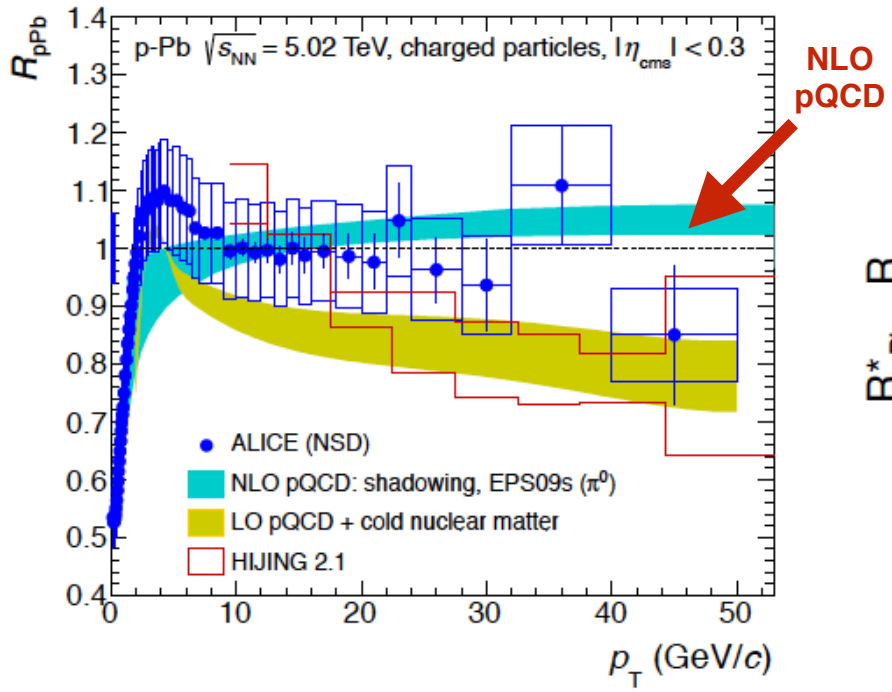
caveat:

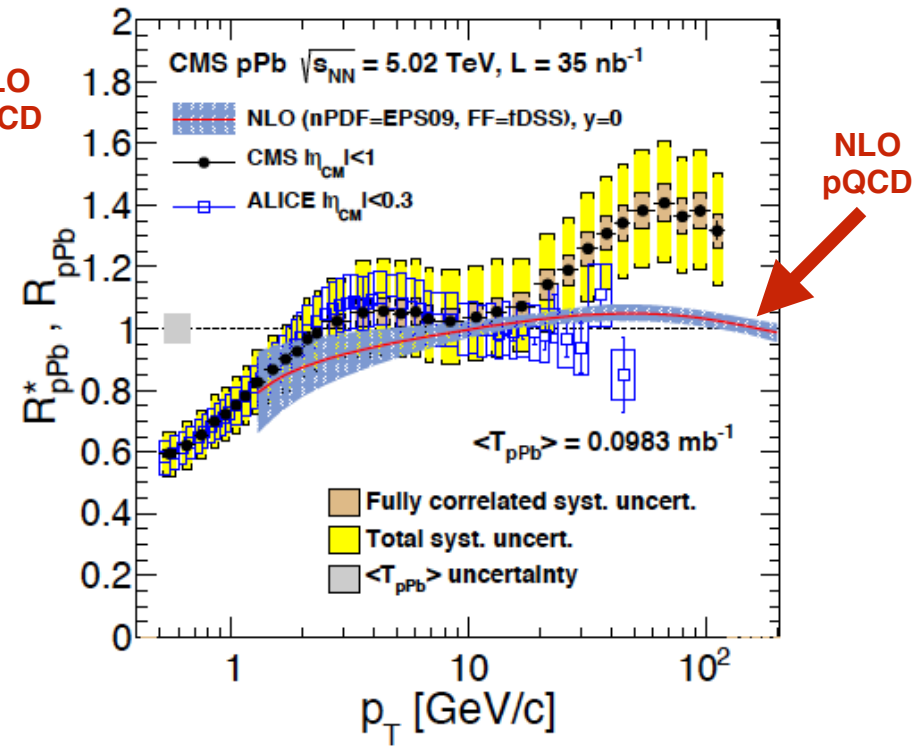
- **observed impact on R_g based on a large weight (20) for RHIC data in fit**
- **w/o the weight little impact on R_g like in DSSZ analysis**

first results from the LHC

H. Paukkunen @ DIS14
A. Sickles @ QM14

some dilemma with charged hadrons: ALICE 1405.2737 vs. CMS 1502.05387



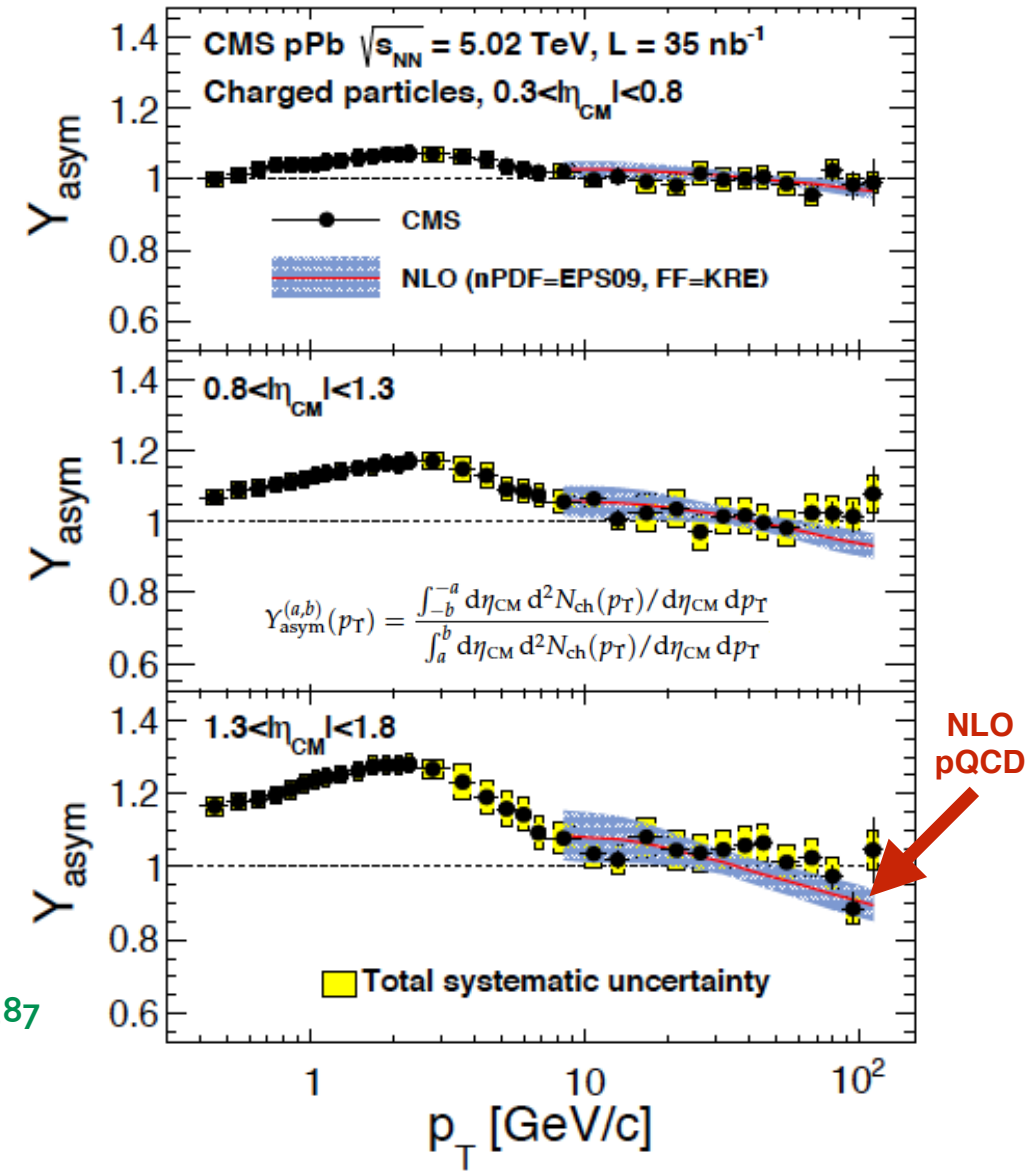


- NLO pQCD (e.g. using EPS 09) does pretty well w.r.t. ALICE data
- large p_T behavior of CMS data impossible to get with nPDFs
- discrepancy partially blamed on missing pp baseline (steeply falling p_T spectrum !)
- R_{pPb} shows little modification for all p_T for reconstructed jets (ALICE, ATLAS, CMS)

that's it??
see, Hard Probes '15

first results from the LHC - cont'd

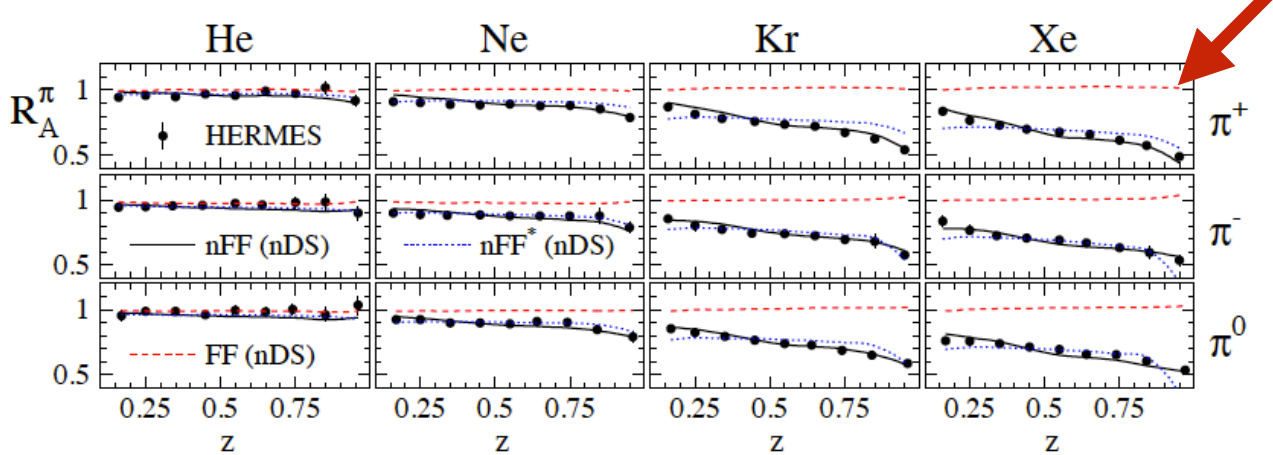
- CMS forward-backward asymmetry (free of pp baseline) agrees well with NLO pQCD



CMS 1502.05387

what about the fragmentation part?

- medium effects known to be large for eA multiplicities **HERMES**



initial-state nPDF only

- cannot be described as an initial-state effect (= nPDFs)
- hadron attenuation increases with A and z
  (rather flat in x and Q^2)

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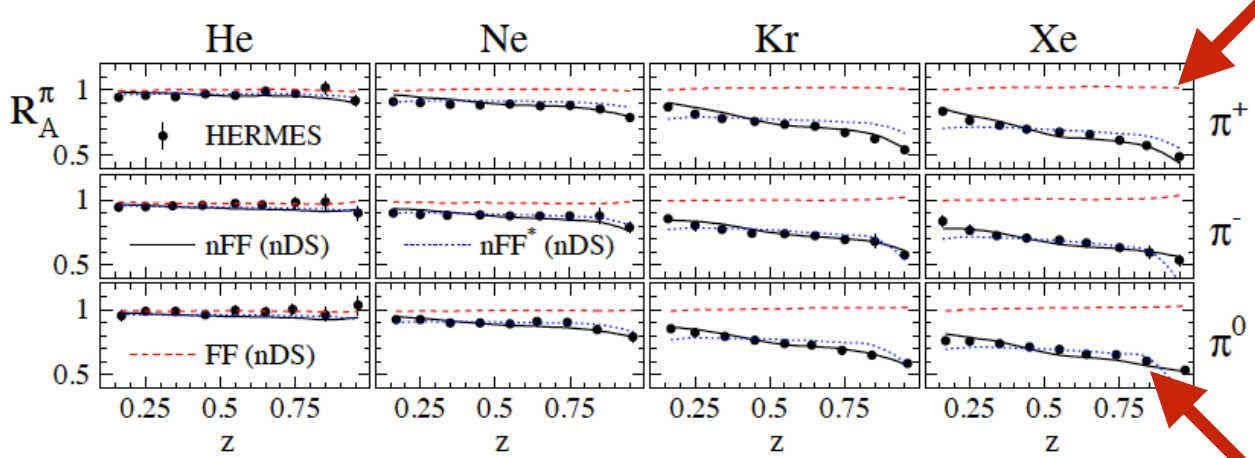


initial-state nPDF only

final-state mod. FF

- cannot be described as an initial-state effect (= nPDFs)
- hadron attenuation increases with A and z (rather flat in x and Q^2)

- bold attempt to model modified FFs (in the "background of a nucleus A") Sassot, MS, Zurita 0912.1311

⚠ don't view this as something too rigorous — FFs are defined w.r.t. to the vacuum — just to estimate potential impact

find:

- suppressed quark-to-pion FF (incr. with A) to fit HERMES data
- enhanced gluon FF around z=0.5 to fit RHIC dA pion data

works very well

- differences in a pA fit can be as large as between EPS and DSSZ (mainly at large p_T)

caveats:

- cannot easily include geometrical effects (path-length in medium, centrality, etc.)

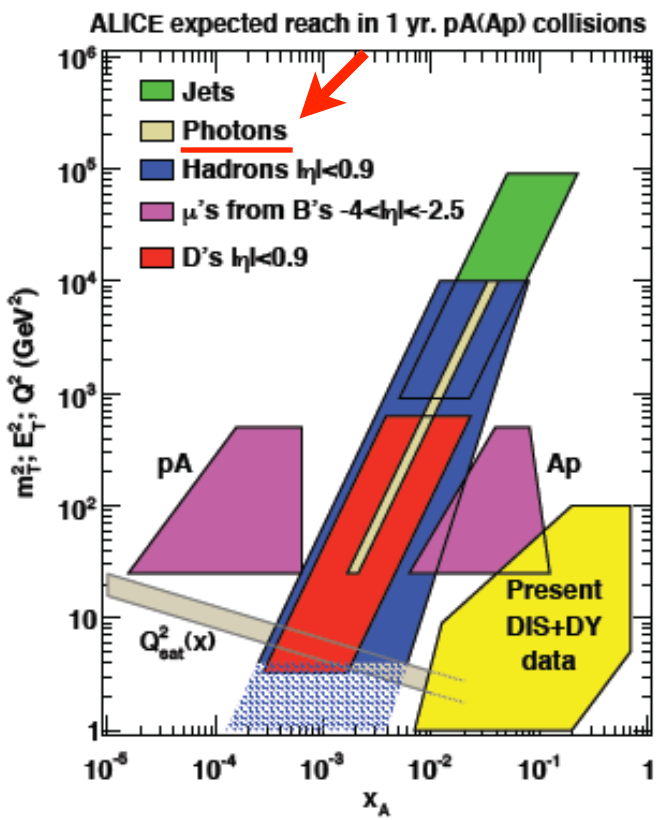
nPDFs in pA: path forward

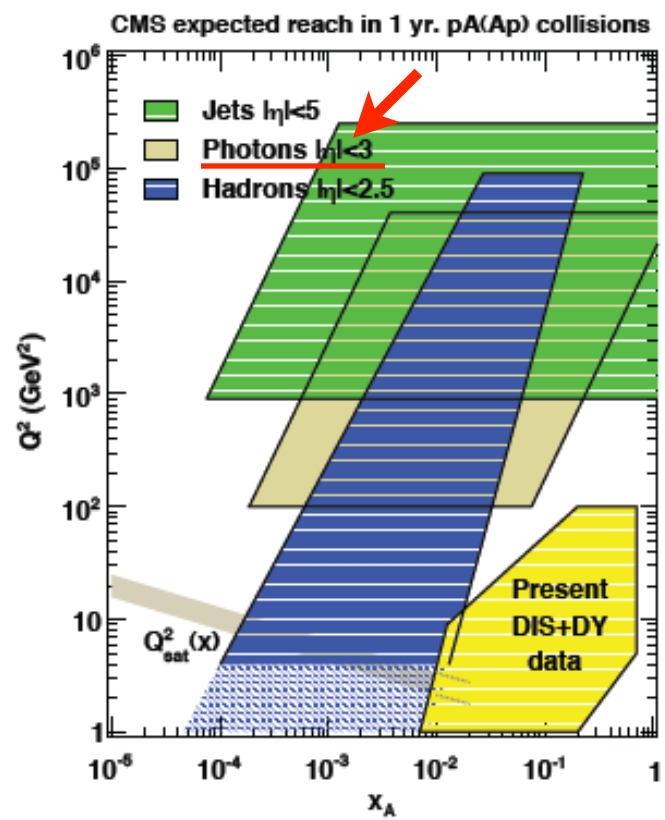
best strategy to unambiguously separate initial and final-state effects

- use only electromagnetic / electroweak probes to further constrain nPDFs

  "price tag": photons, W/Z bosons, DY are all rare probes; need to unfold "isospin effect"

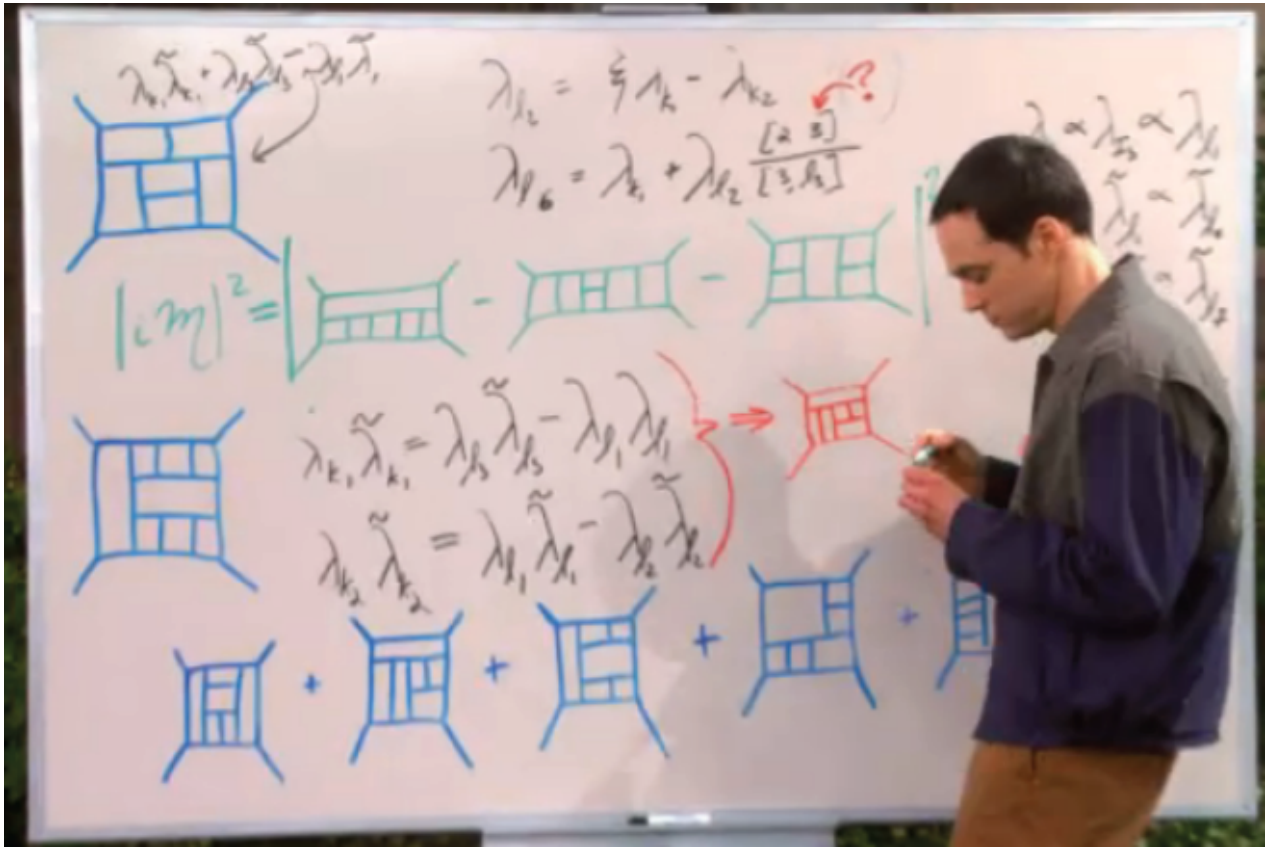
- next, check how well pions, jets, and heavy quarks are described





Salgado et al., 1105.3919

5



some recent theoretical developments

inclusive hadrons vs. jets

QCD processes are the same for 1-jet and 1-hadron yields - where's the difference?

- **jets don't distinguish quarks and gluons in final-state**

  —> 16 channels for identified hadrons collapse to 6 for jets

$$
\begin{aligned}
qq' &\to \text{jet} + X \\
q\bar{q}' &\to \text{jet} + X \\
q\bar{q} &\to \text{jet} + X \\
qq &\to \text{jet} + X \\
qg &\to \text{jet} + X \\
gg &\to \text{jet} + X
\end{aligned}
$$

summed over all partons

- **collinear singularities are not resolved within a "cone"**

  —> geometric definition has to match experimental choice (anti-k_T, cone, ...)

  —> diverges logarithmically with jet "size" R: $d\sigma^{\text{jet}} \simeq A\log(R) + B + \mathcal{O}(R^2)$

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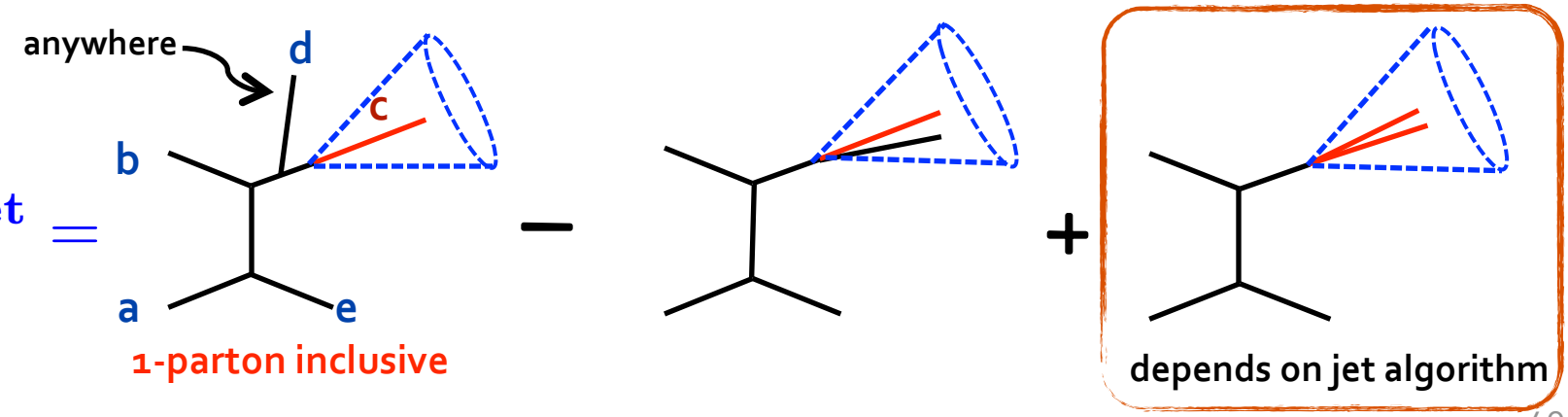
- close resemblance to hadrons manifest in small-jet approximation

Jager, MS, Vogelsang; Mukherjee, Vogelsang

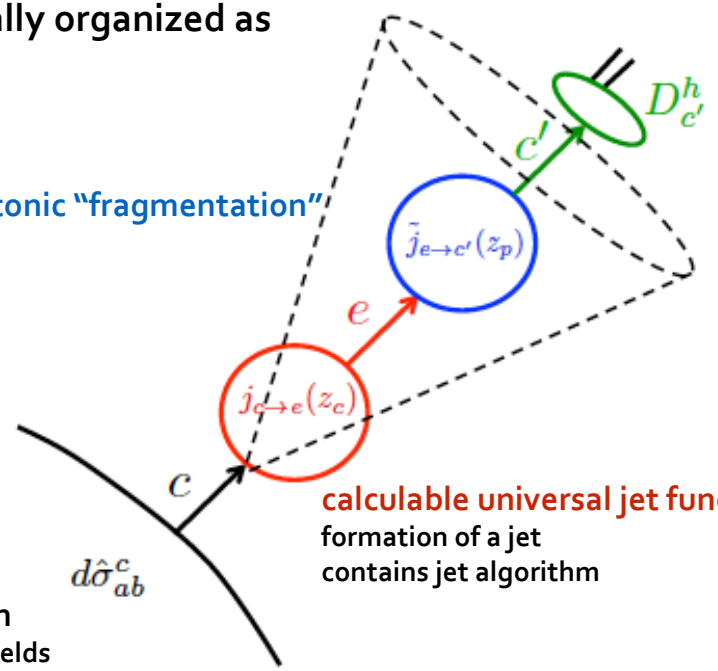
$$\mathbf{d}\sigma^{\mathbf{1-jet}} =$$



hadrons inside a jet

observable: $$\frac{d\sigma^{pp\to(\mathrm{jet}\,H)+X}}{dp_T^{\mathrm{jet}}\,d\eta^{\mathrm{jet}}\,dz_H}$$ identified hadron in a jet with $$z_H \equiv \frac{p_T^H}{p_T^{\mathrm{jet}}}$$

pQCD calculation can be schematically organized as



standard parton-to-hadron FF
produces the observed hadron

calculable universal partonic "fragmentation"
happens inside the jet

calculable universal jet function
formation of a jet
contains jet algorithm

single-incl. parton cross section
same as used for inclusive hadron yields

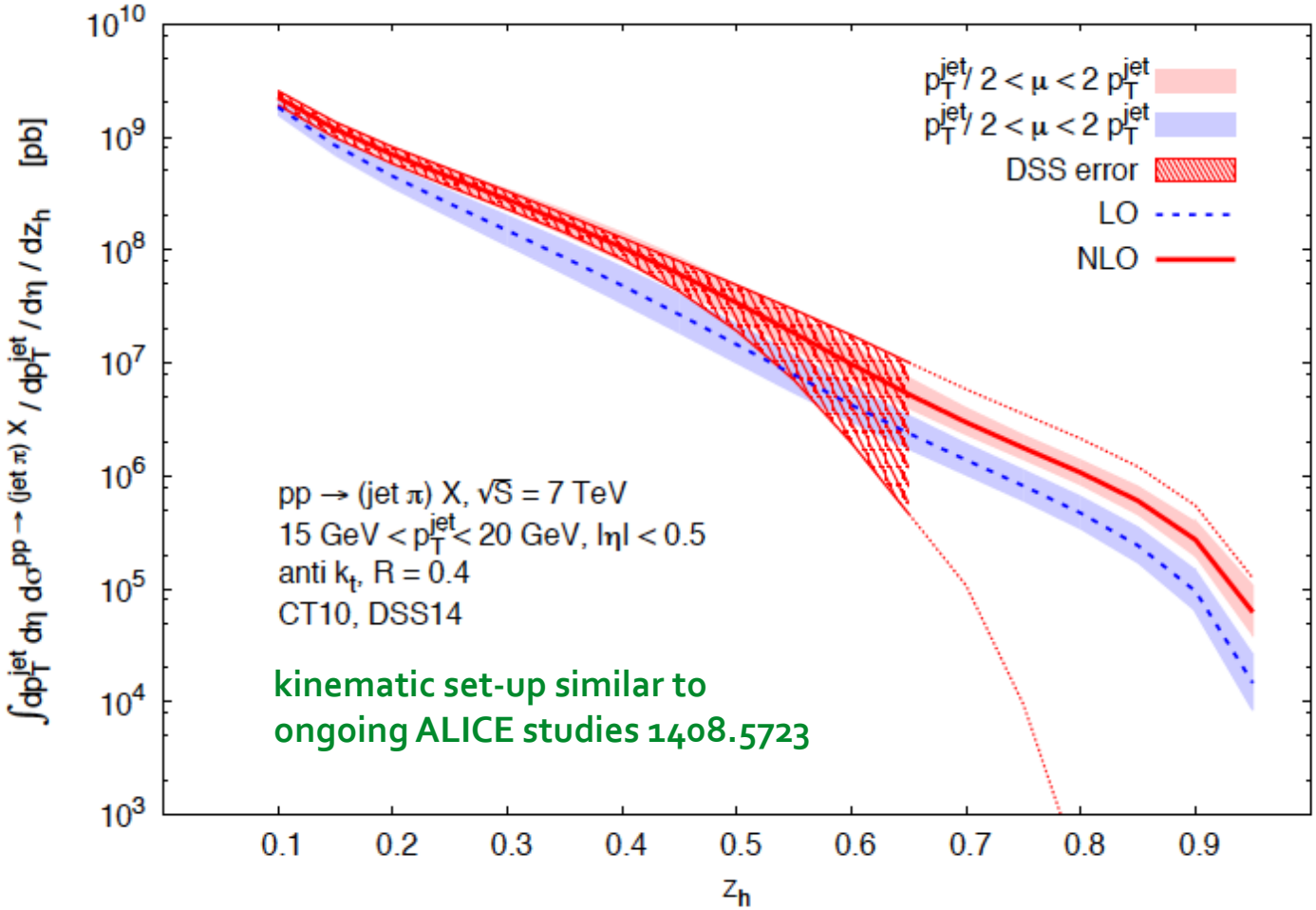
considerable theoretical activity recently:

MC techniques: Procura, Stewart; Jain et al.; Arleo et al.; Ritzmann, Waalewijn, ...
anal. calc. (small jet approx.): Kaufmann, Mukherjee, Vogelsang 1506.01415

hadrons inside a jet - application

interesting observable as it gives a better handle on momentum fraction z in FFs

Kaufmann, Mukherjee, Vogelsang 1506.01415

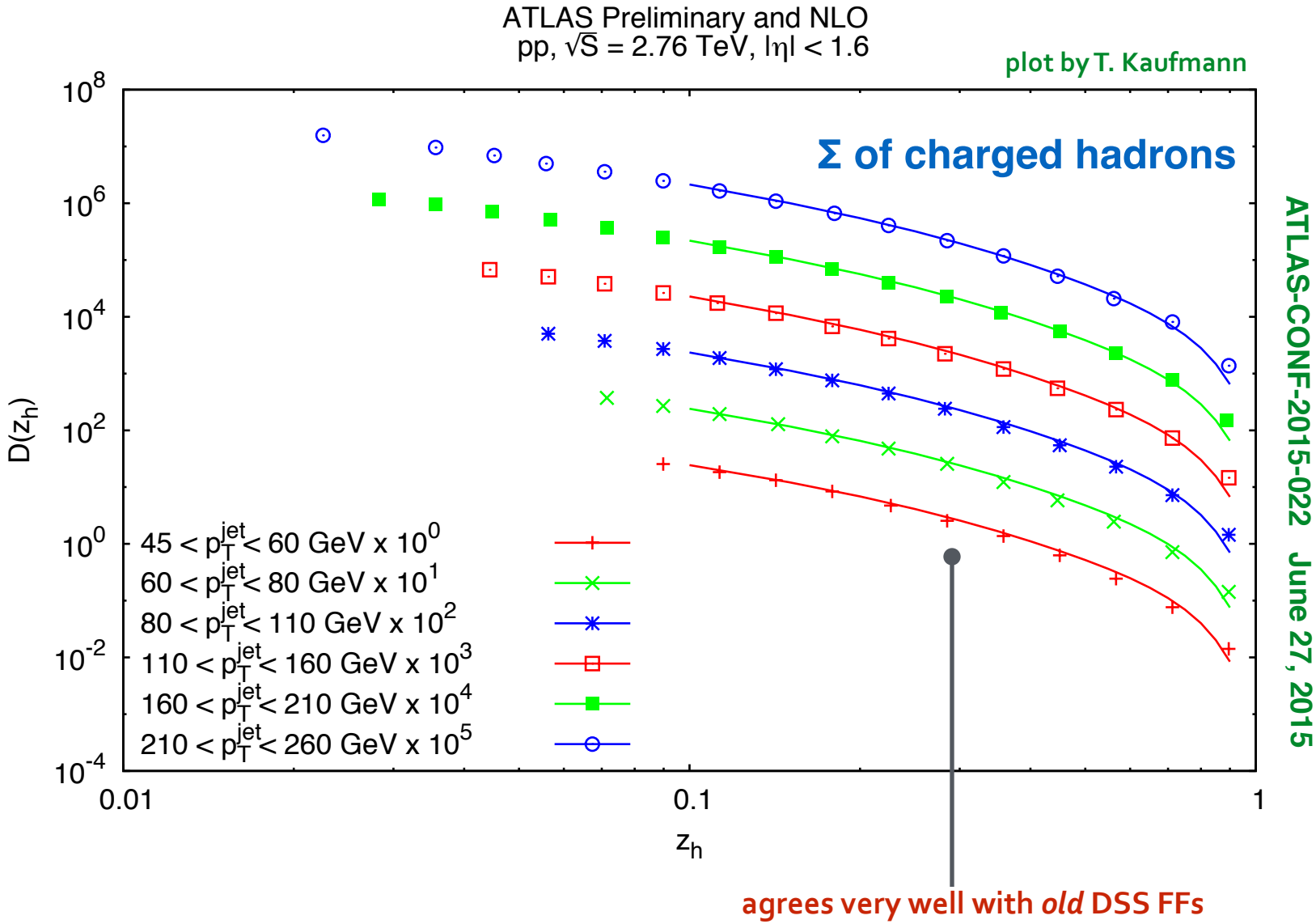


kinematic set-up similar to ongoing ALICE studies 1408.5723

great prospects to map out gluon FF at high z

where applicable, NLO pQCD approach describes also CMS data JHEP1210 (2012) 087

recent ATLAS result (a new puzzle?)



agrees very well with *old* DSS FFs

?! recall: CMS chg. hadron cross section does NOT ?!

towards FFs @ NNLO

work in progress: D. Anderle, F. Ringer, MS

WHY ? it's all about precision and controlling theoretical uncertainties ...

- e.g., truncation of series leads to residual μ dependence $\frac{d}{d\ln\mu}\sum_{n=1}^{N} d\sigma(\alpha_s^n,\ldots) = \mathcal{O}(\alpha_s^{N+1})$

  —> blessing in disguise: μ dependence is estimator of missing higher orders !

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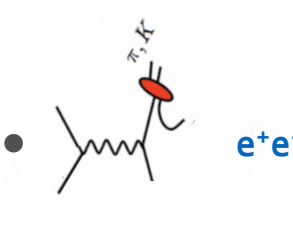
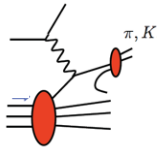
What is available @ NNLO ?

- timelike evolution kernels Mitov, Moch, Vogt (NS, '06); Almasy, Mitov,Moch, Vogt (SIN, '12)
- 

  e^+e^- coeff. fct's [except for $O(\alpha_s^3)$ F_L] Rijken, van Neerven (x-space '96); Mitov, Moch ; Blumlein , Ravindran (n-space, '06)
- 

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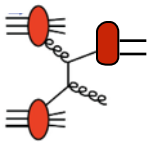
- 
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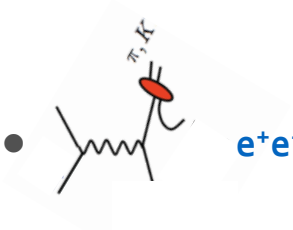

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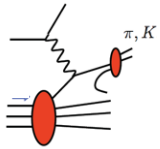

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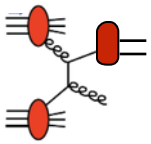

- pp coeff. fct's only NLO

can resort to NLL results (expanded to NNLO)

SIDIS: Anderle, Ringer, Vogelsang '12

pp: Hinderer, Ringer, Sterman, Vogelsang (soon)

all-order resummations

Sterman; Catani, Trentadue; Kidonakis, Sterman; ....

- **main idea:** inhibited radiation near exclusive boundary; IR cancellation leaves large logs
  - example DIS: $C_q \sim e_q^2\left[\delta(1-x) + a_s C_F\left\{(1+x^2)\left(\frac{\ln(1-x)}{1-x}\right)_+ - \frac{3}{2}\frac{1}{(1-x)_+} + \ldots\right\}\right]$

    $\frac{1}{2}\log^2(1-x)\, q(x)$ in convolution with PDFs
  - well defined class of higher order corrections: $a_s^k L^{2k}, a_s^k L^{2k-1}, \ldots$ at kth order

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  - well defined class of higher order corrections: $a_s^k L^{2k}, a_s^k L^{2k-1}, \ldots$ at kth order

- **terminology:** **logs can be systematically resummed to all orders** (-> exponentiated)

Resummation \ Fixed Order						
LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	...	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...
	LL		NLL		NNLL	

evolution of FFs @ NNLO

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- **developed a NNLO evolution code**
  - based on NNLO PDF evolution **PEGASUS** (A. Vogt '05) in Mellin n space
  - other recent effort **APFEL/MELA** (Bertone et al.,'13 + '14)

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- **recall: DGLAP solution not unique beyond LO**
  - need to employ expansion around LO solution

LO evolution operator $\boldsymbol{q}_{\rm LO}(N, a_{\rm s}, N) = \left(\frac{a_{\rm s}}{a_0}\right)^{-\boldsymbol{R}_0(N)} \boldsymbol{q}(N, a_0) \equiv \boldsymbol{L}(N, a_{\rm s}, a_0)\, \boldsymbol{q}(N, a_0)$

$$\begin{aligned}
\boldsymbol{q}(N, a_{\rm s}) &= \boldsymbol{U}(N, a_{\rm s})\, \boldsymbol{L}(N, a_{\rm s}, a_0)\, \boldsymbol{U}^{-1}(N, a_0)\, \boldsymbol{q}(N, a_0) \\
&= \left[1 + \sum_{k=1}^{\infty} a_{\rm s}^k\, \boldsymbol{U}_k(N)\right] \boldsymbol{L}(a_{\rm s}, a_0, N) \left[1 + \sum_{k=1}^{\infty} a_0^k\, \boldsymbol{U}_k(N)\right]^{-1} \boldsymbol{q}(a_0, N)
\end{aligned}$$

evolution matrix U_k (β_{QCD}, P_{ij}, l<=k)
recursively defined through commutation relations

normalizes to unity for $\alpha_s = \alpha_o$
cancels spurious poles in U_k

- various ways to define N^mLO solution which differ by terms O(n>m)
- usually neglected **theoretical ambiguity** ! [can be %-ish for PDFs @ small x]

evolution of FFs @ NNLO

work in progress: D. Anderle, F. Ringer, MS

- **truncated n space solution**
  - retain only terms at desired order n

$$
\begin{aligned}
\boldsymbol{q}_{\mathrm{N^3LO}}(a_s) \;=\; & \Big[\boldsymbol{L} + a_s \boldsymbol{U}_1 \boldsymbol{L} - a_0 \boldsymbol{L} \boldsymbol{U}_1 && \text{NLO} \\
& + a_s^2 \boldsymbol{U}_2 \boldsymbol{L} - a_s a_0 \boldsymbol{U}_1 \boldsymbol{L} \boldsymbol{U}_1 + a_0^2 \boldsymbol{L} \left(\boldsymbol{U}_1^2 - \boldsymbol{U}_2\right) && \text{NNLO} \\
& + a_s^3 \boldsymbol{U}_3 \boldsymbol{L} - a_s^2 a_0 \boldsymbol{U}_2 \boldsymbol{L} \boldsymbol{U}_1 + a_s a_0^2 \boldsymbol{U}_1 \boldsymbol{L} \left(\boldsymbol{U}_1^2 - \boldsymbol{U}_2\right) && \text{NNNLO} \\
& - a_0^3 \boldsymbol{L} \left(\boldsymbol{U}_1^3 - \boldsymbol{U}_1 \boldsymbol{U}_2 - \boldsymbol{U}_1 \boldsymbol{U}_2 + \boldsymbol{U}_3\right)\Big] \boldsymbol{q}(a_0) \;,
\end{aligned}
$$

  - does not solve DGLAP eqs. literally, only after expansion to order n

- **iterated n space solution**
  - at order n keep everything which can be computed with β_n and P_n
  - matches with direct x space solution (to compare different codes !)
  - introduces more scheme dependent terms beyond order n

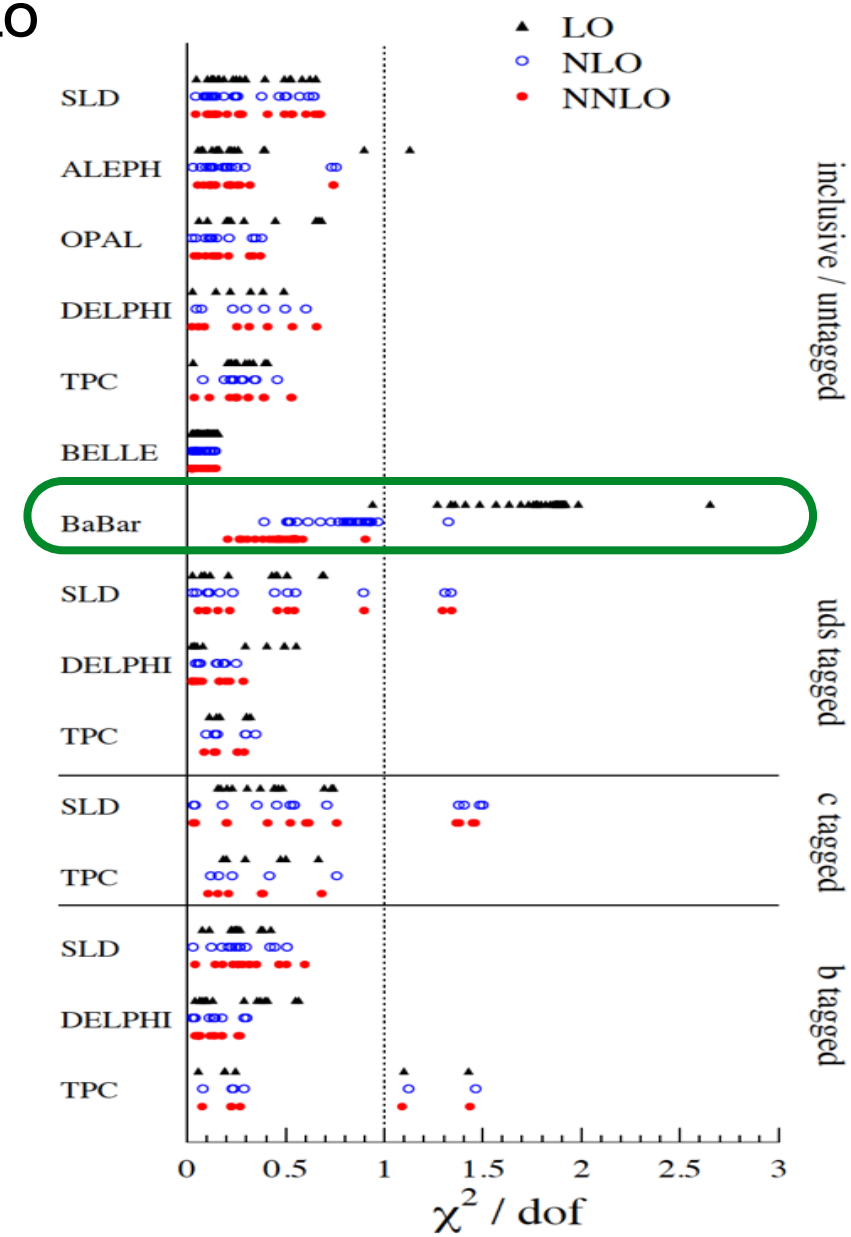
e^+e^- analysis @ NNLO

work in progress: D. Anderle, F. Ringer, MS

- performed new fits of e^+e^- data up to NNLO

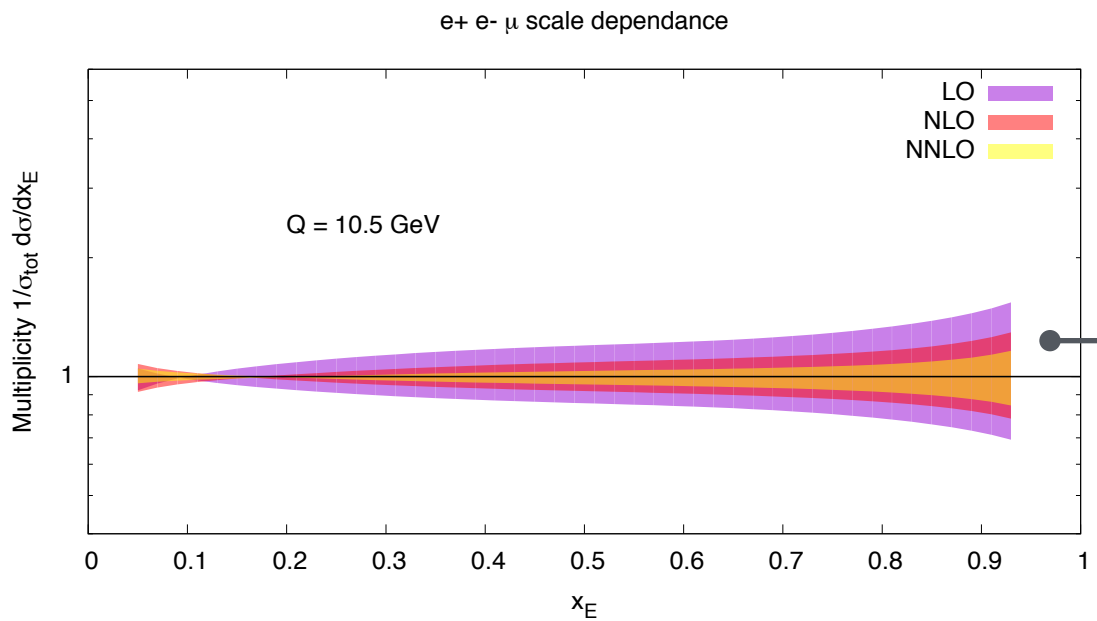
χ^2 of the fit [280 data points]

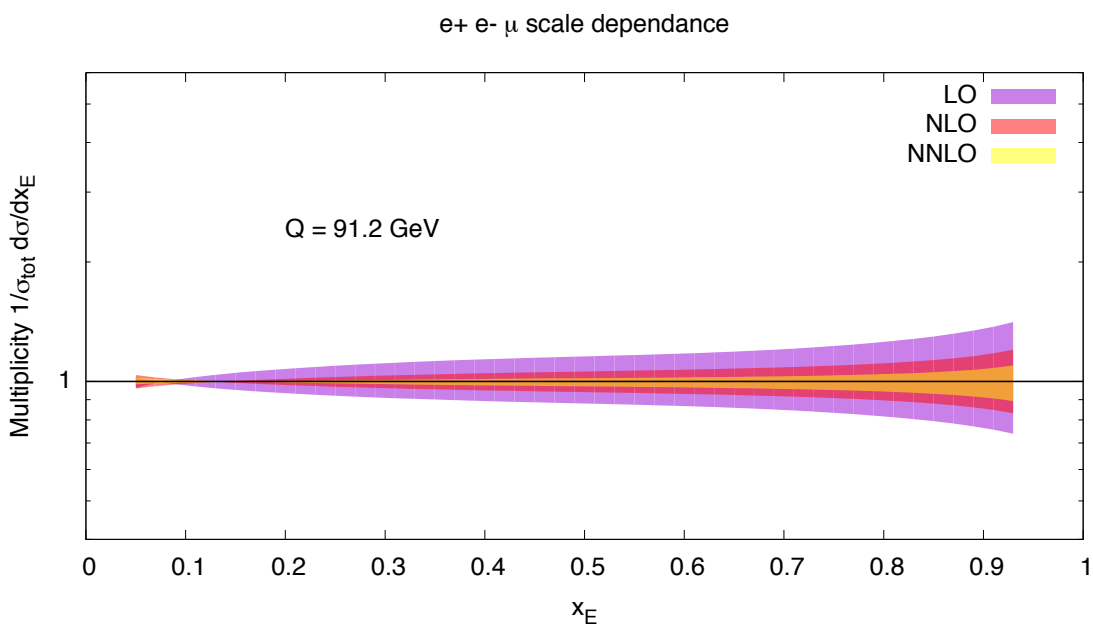
LO	241
NLO	190
NNLO	175



appetizer: scale uncertainty @ NNLO

work in progress: D. Anderle, F. Ringer, MS





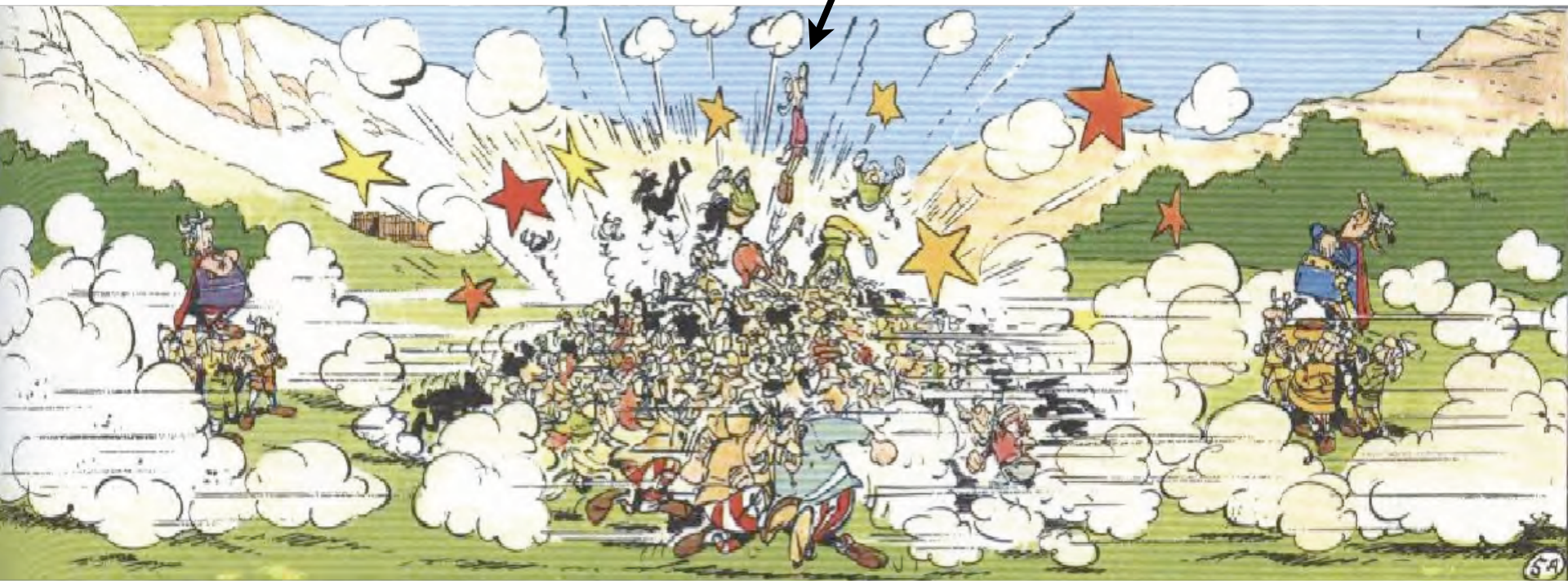
significantly reduced theoretical errors

large x_E : resummations important will be studied/included

executive summary

pQCD & factorization: a quantitative tool for the most energetic stuff emerging from violent collisions

high-p_T —> factorization !



LHC & RHIC data will further our understanding of nucleons, nuclei, and hadronization and possible limitations of the pQCD framework based on factorization

NNLO precision emerging as the new standard - stay tuned