QCD experimental summary

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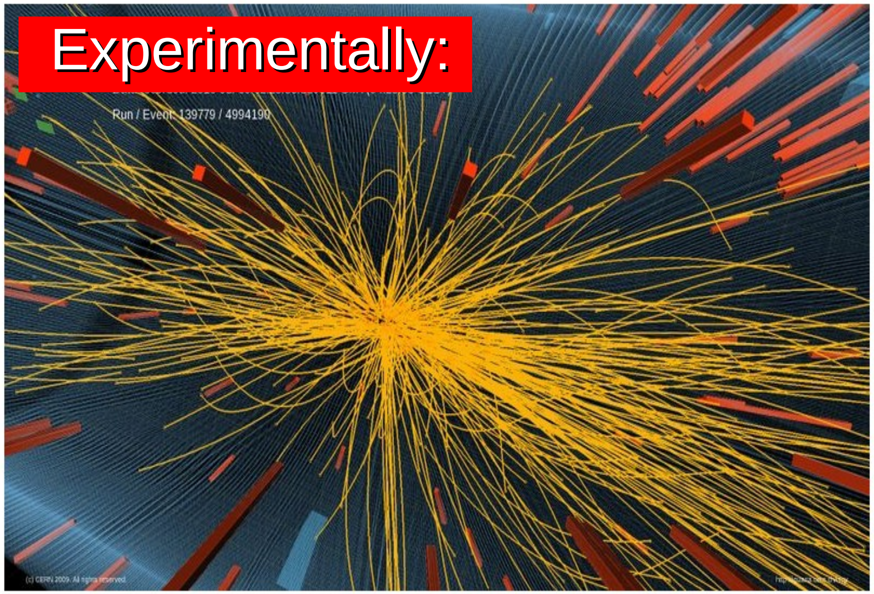
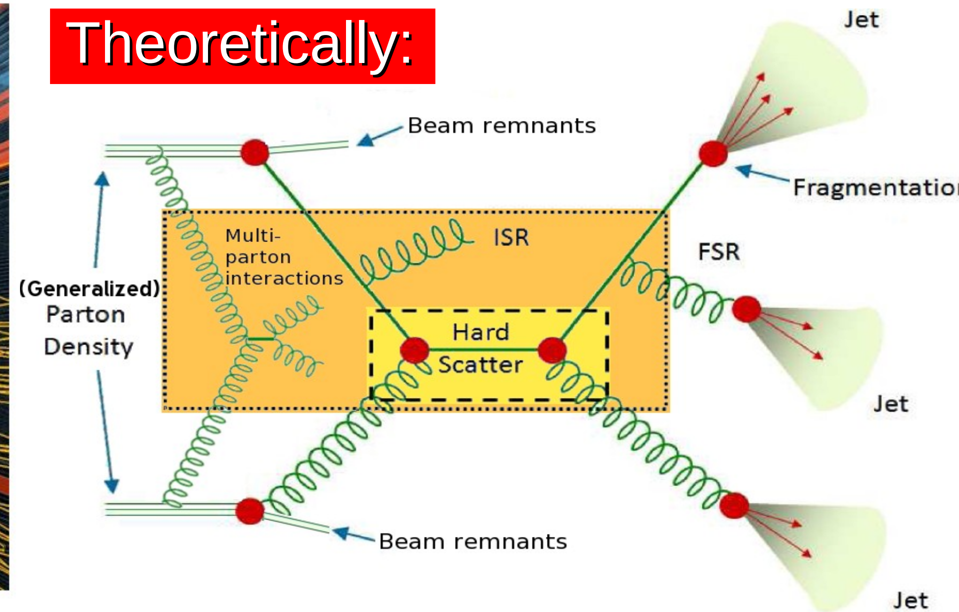
CERN

Prague/Virtual, 4th Aug. 2020

Virtually all LHC p-p physics “is” QCD physics

- Proton-proton collision at the LHC = Full QCD at work:



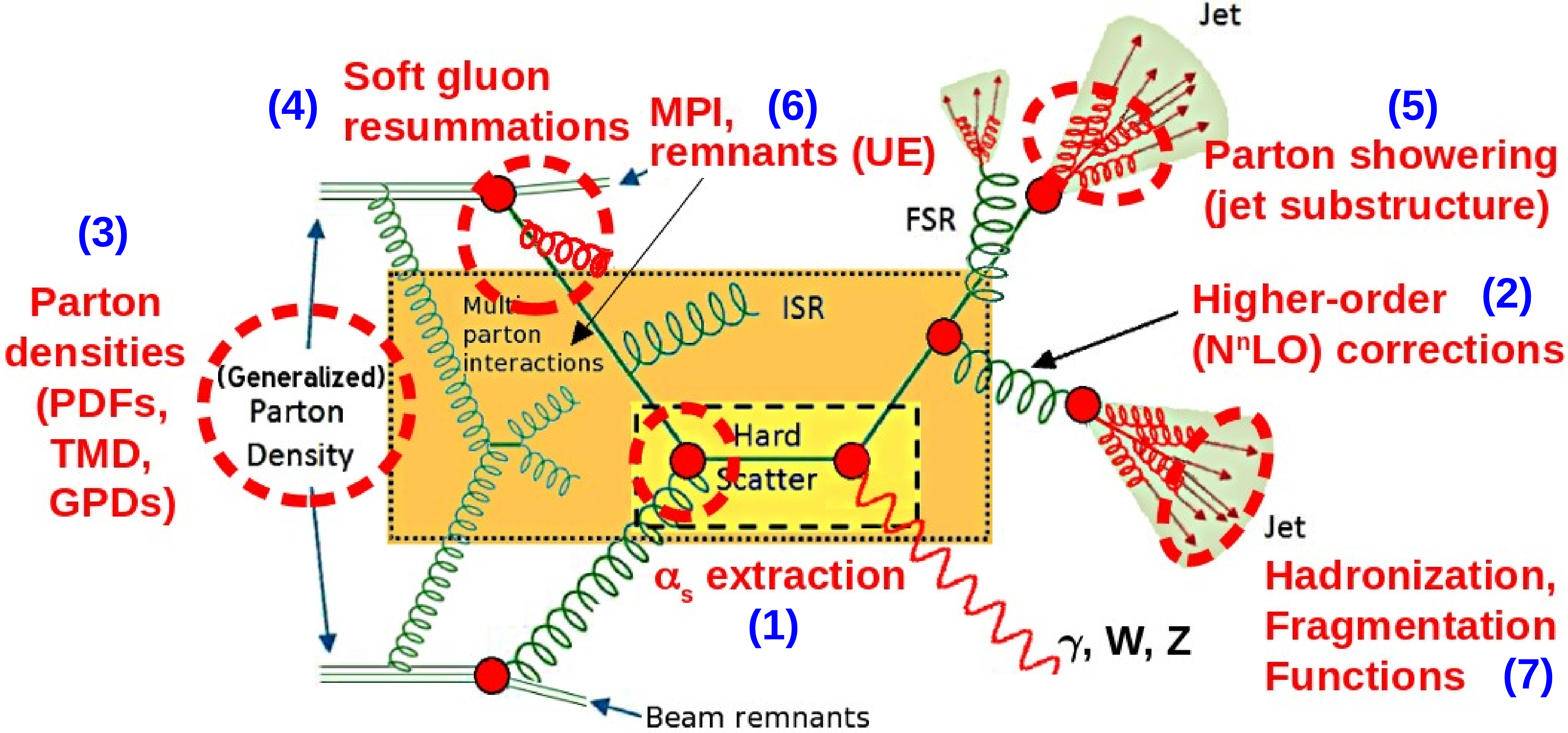


- <u>All LHC observables</u> depend chiefly on a precise EXP/TH control of QCD:

i) BSM TeV-heavy objects on precise high-x PDF, instantons on MB,...
ii) Higgs b,c partial widths: on accurate jet tagging, precise α_s coupling, …
iii) W mass: on precise mid-x PDF, low p_T resummations, intrinsic k_T, …
iv) Top mass: on jet grooming, α_s coupling, FS colour reconnection, …
….

Topical organization of the talk

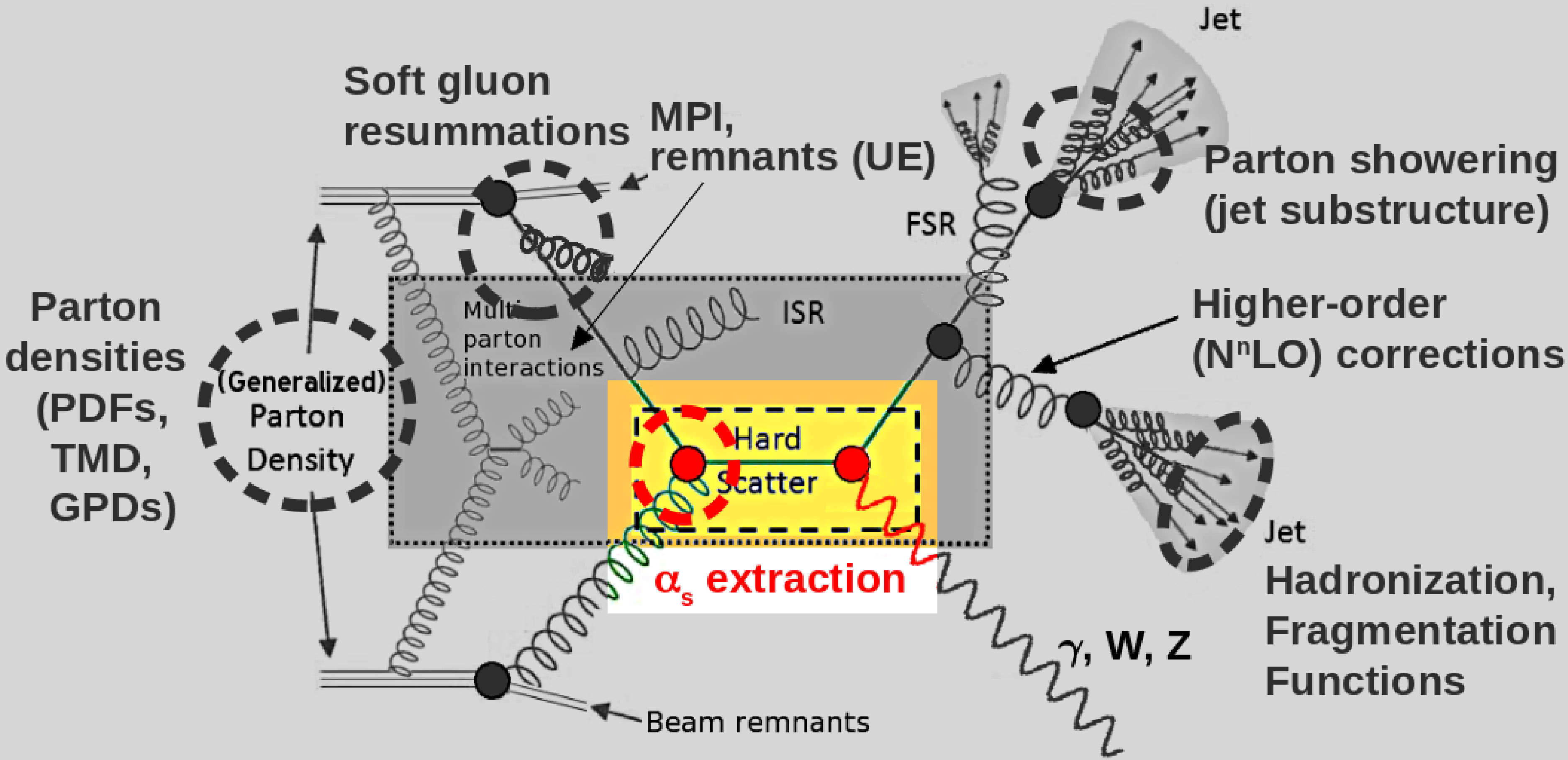
- Proton-proton collision at the LHC = Full QCD at work:



DISCLAIMER: This talk cannot cover all nice hundreds QCD exp. results presented at ICHEP'20 (but, hopefully, a representative selection of them).

(1) Strong coupling constant

- Typical proton-proton collision at the LHC:

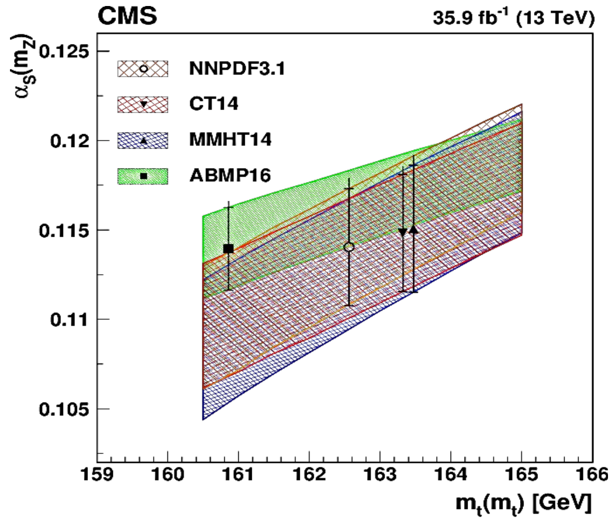


Role of the strong coupling α_s well beyond QCD

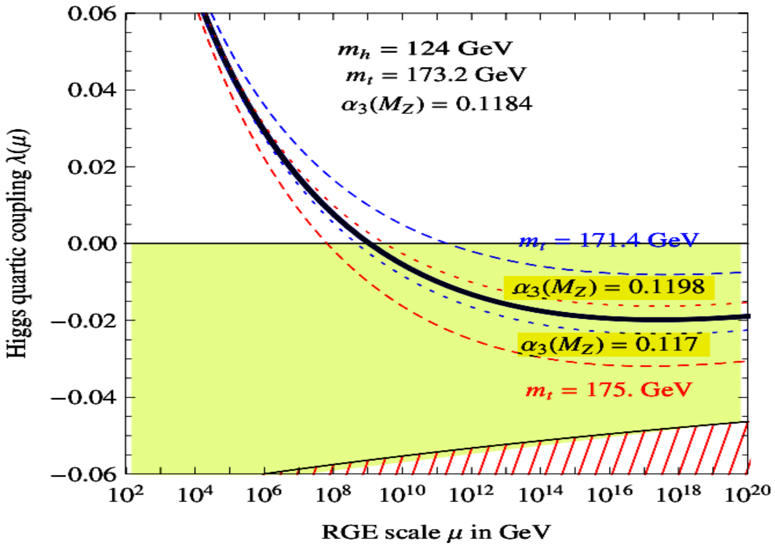
- Impacts all theoretical x-sections & decays (Higgs), top mass extractions:

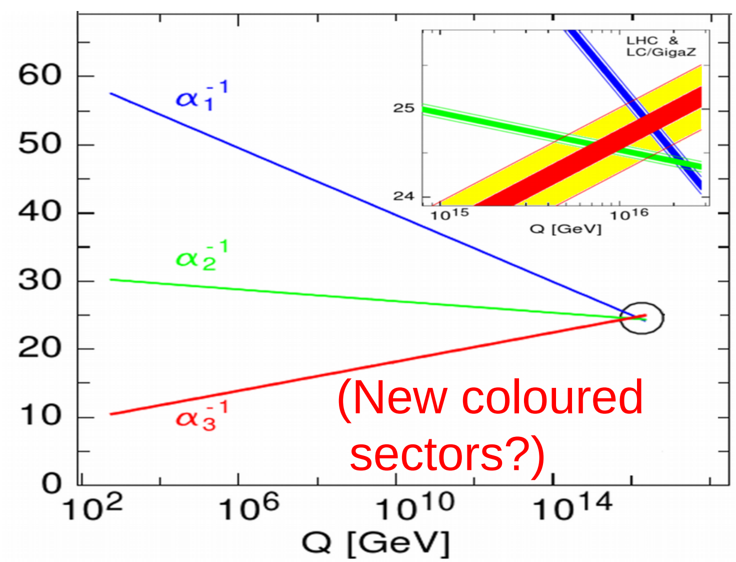
Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	$\pm$ 3.7	-6.2 +7.4	-2.61 + 0.32
ttH	0.611	$\pm$ 3.0	$\pm$ 8.9	-9.3 + 5.9

Channel	M_H[GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
$H \to c\bar{c}$	126	$\pm$ 7.1	$\pm$ 0.1%	$\pm$ 2.3 %
$H \to gg$	126	$\pm$ 4.1	$\pm$ 0.1%	$\pm$ 0 %



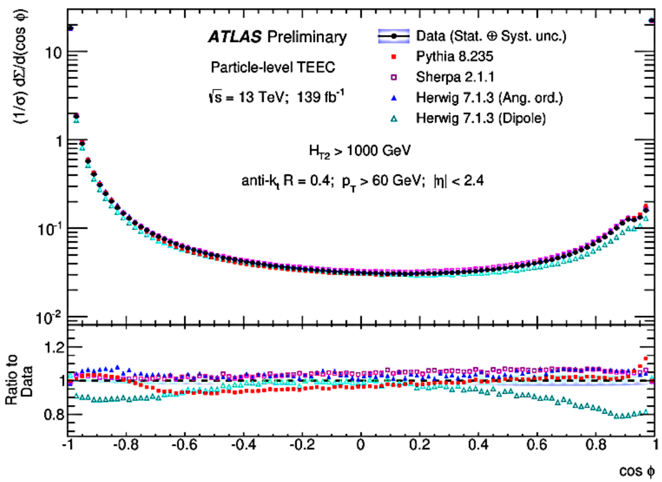
- Impacts physics approaching Planck scale: EW vacuum stability, GUT

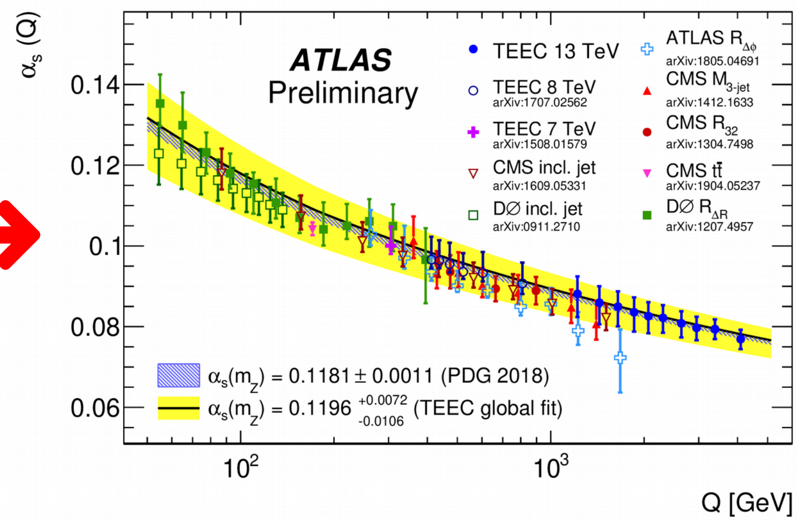




New QCD coupling extractions at the LHC

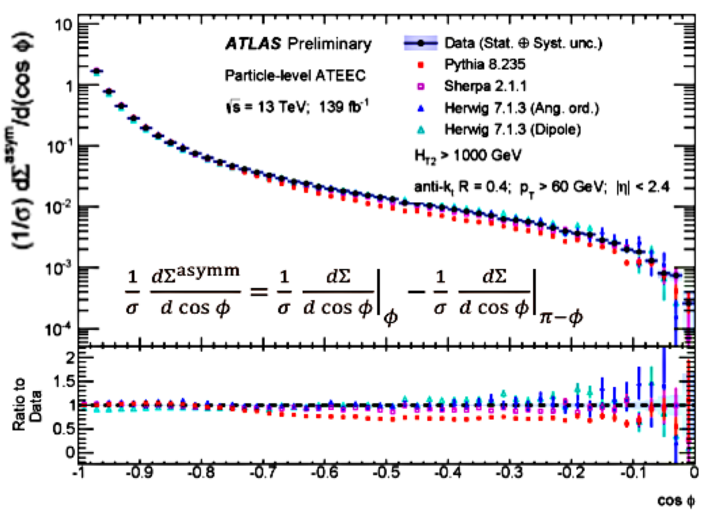
- Extracted α_s=0.1196$^{+0.0072}_{+0.0106}$ (NLO,±8%) via transv. E-E corrs. in multijet evts:



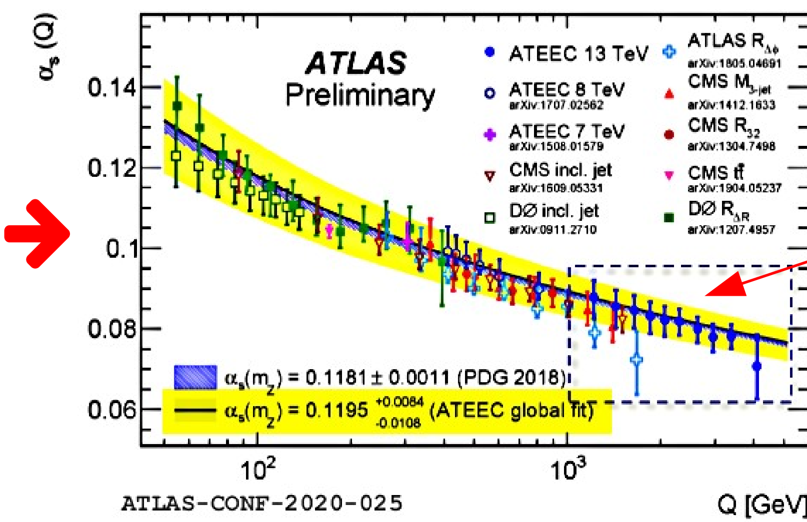


[P.Loch/ ATLAS]

- Extracted α_s=0.1195$^{+0.0084}_{+0.0108}$ (NLO,±8%) via TEEC azimuthal asymmetries:



$$\frac{1}{\sigma}\frac{d\Sigma^{\rm asymm}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

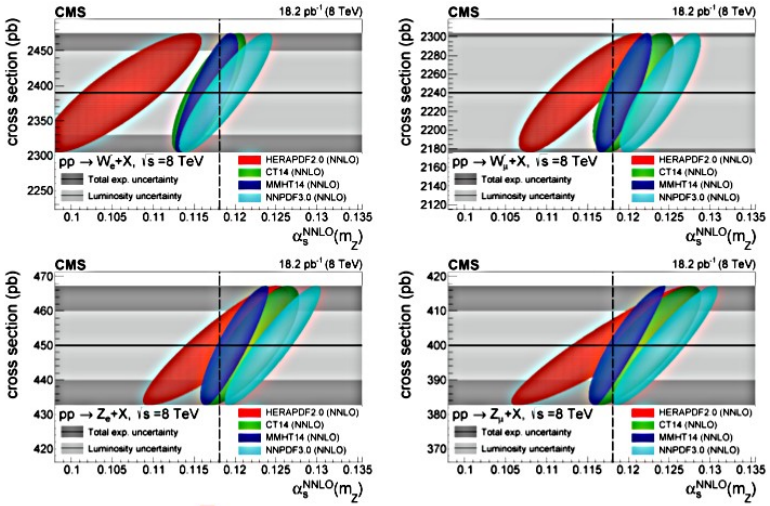


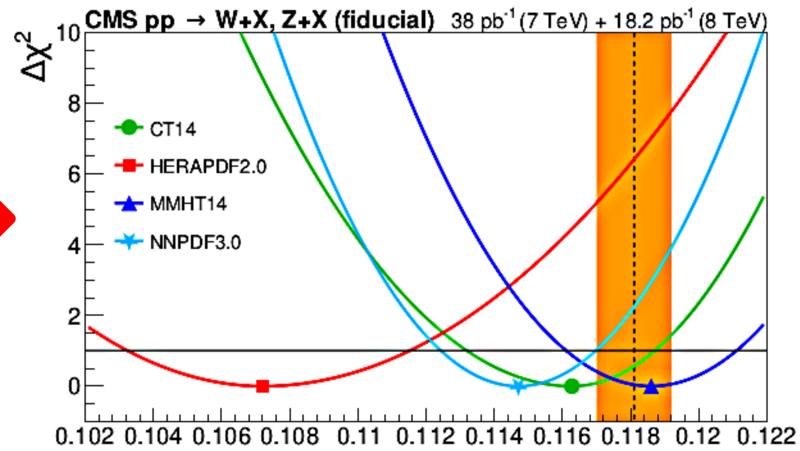
ATLAS-CONF-2020-025

α_s running tested up to 4 TeV!

New QCD coupling extractions at the LHC

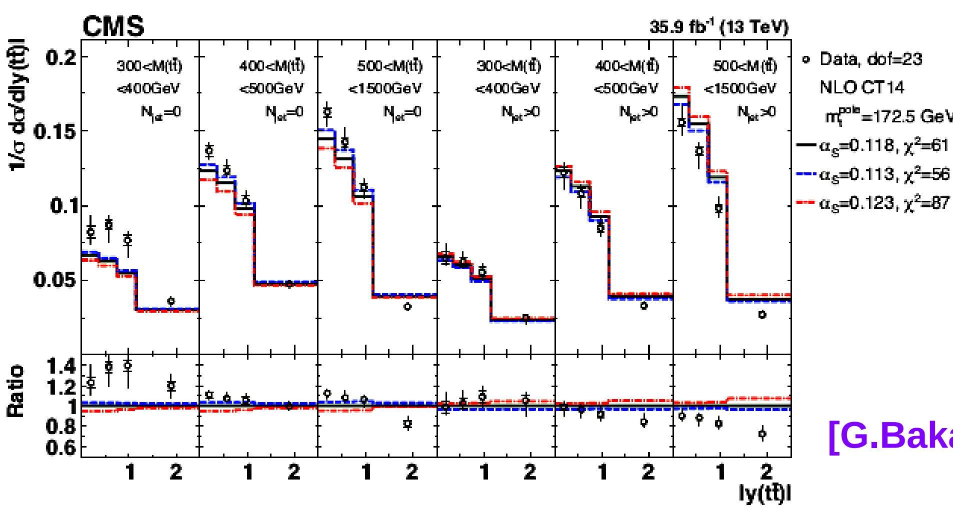
- Extracted α_s=0.1175±0.0026 (**NNLO,**±2.3%) via 12 precise W,Z x-sections:

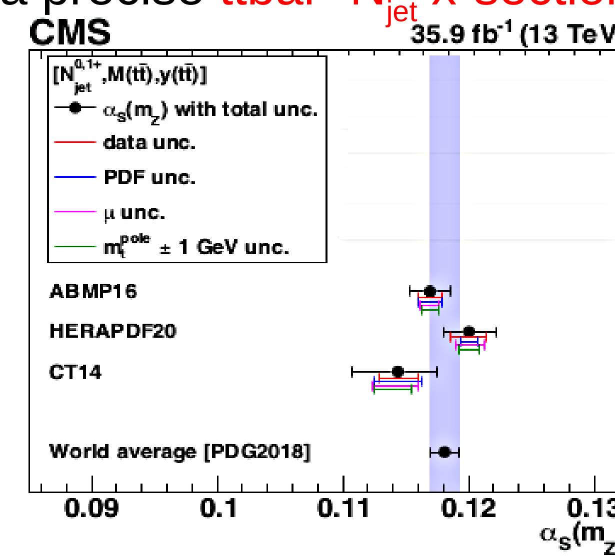




[I.Gorbunov/CMS]

- Extracted α_s=0.1135±0.0020 (NLO, PDF dep.) via precise ttbar+N_{jet} x-sections:

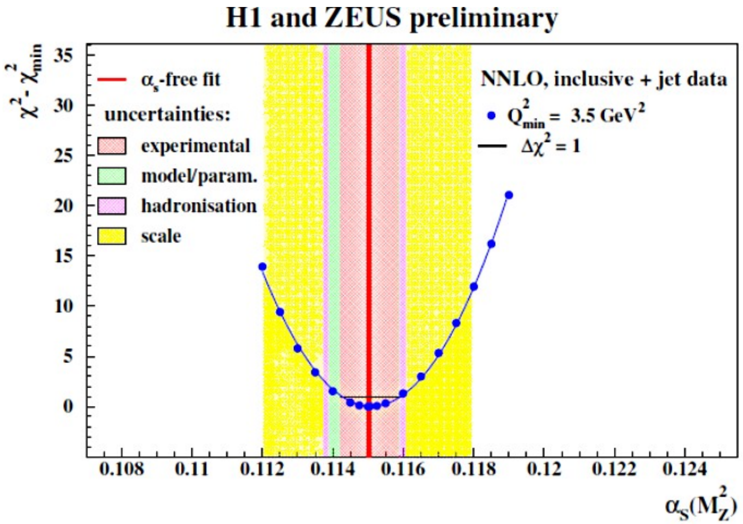


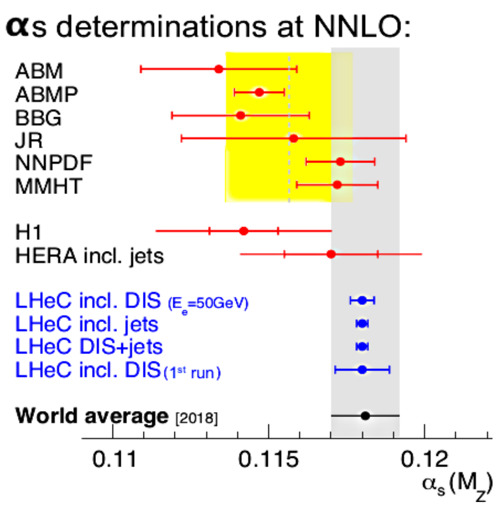


[G.Bakas/CMS]

New QCD coupling extraction in DIS

- Extracted α_s=0.1150±0.0029 (**NNLO**,±2.5%) via global H1/ZEUS DIS+jets fit:





[A.Sarkar/H1&ZEUS]

Inclusion of DIS jet data leads to larger & more precise α_s

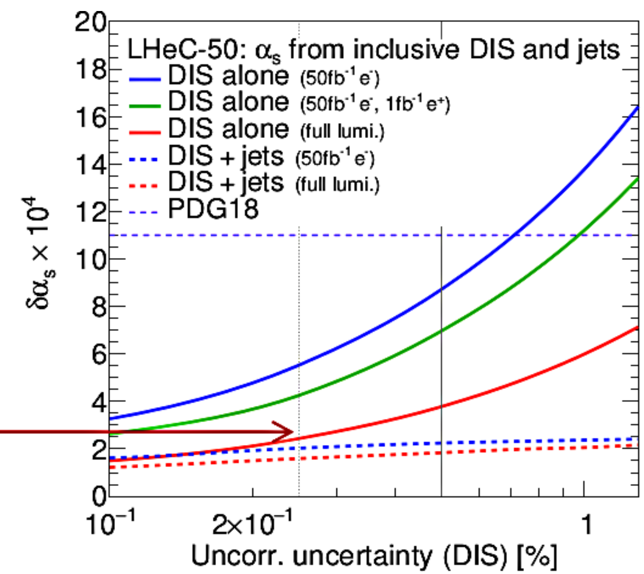
(HERAPDF: α_s=0.108±0.010 with incl. DIS alone)

- Extractions with x10 times smaller uncertainty (±0.2%) only reachable at new DIS machines such as LHeC:

[C.Gwenlan/LHeC]

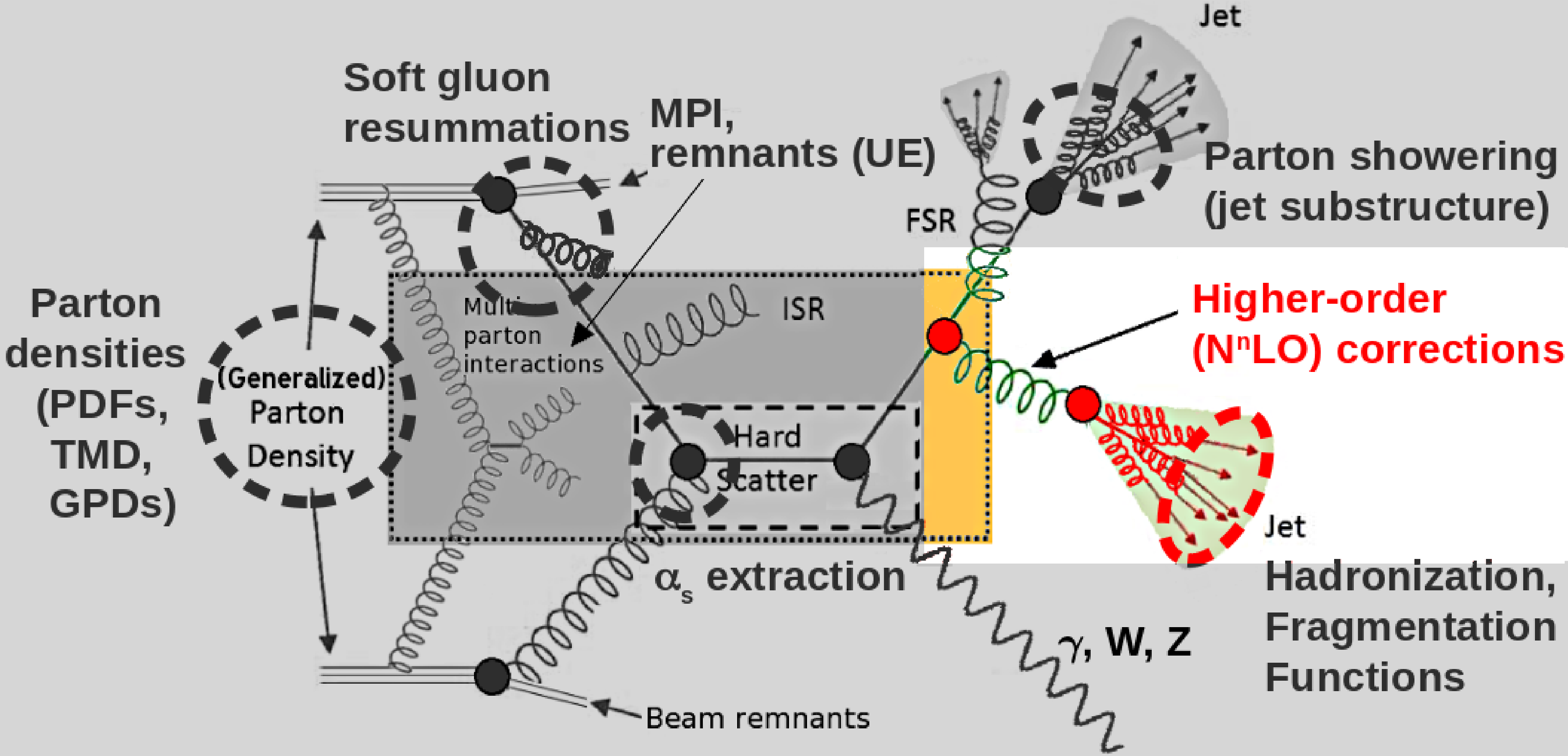
- **αs** from inclusive NC/CC DIS:
- simultaneous determination of **pdfs** and **αs** in **NNLO QCD** fit
- **3** LHeC scenarios:
- LHeC 1st Run (50 fb^{-1} e-p)
- plus 1 fb^{-1} positron data
- full inclusive LHeC dataset (1 ab^{-1})

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$



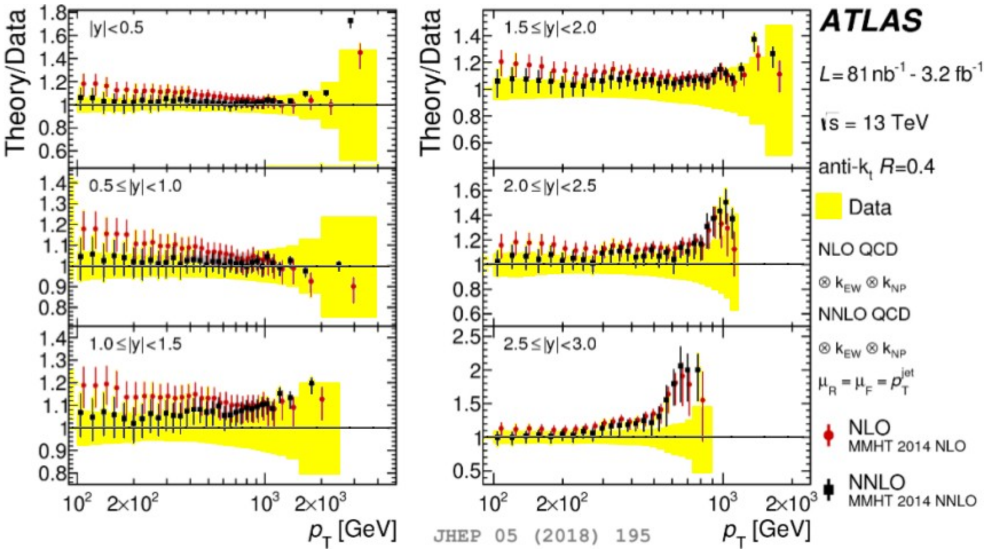
(2) Higher-order pQCD corrections

- Typical proton-proton collision at the LHC:

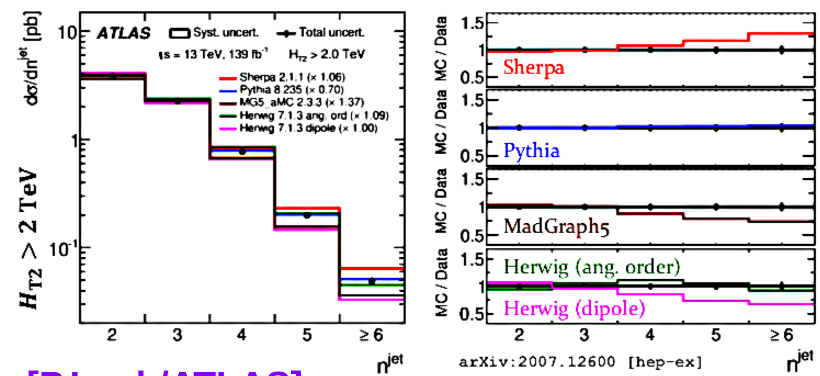


Data vs. pQCD at N^nLO: Jets, γ, γ+jets

- New **NNLO** jet calc. improve data-theory accord. Scale uncertainties reduced.

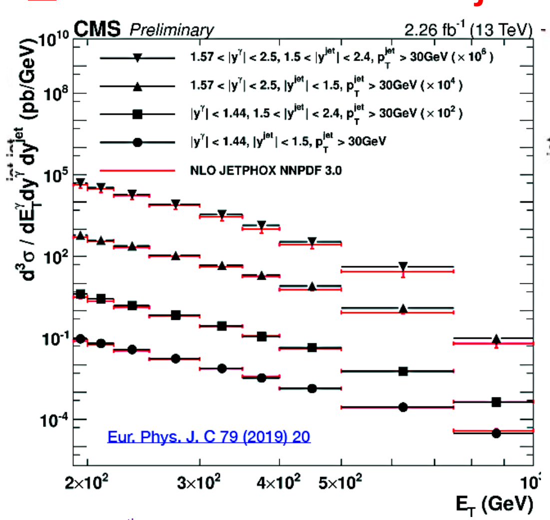


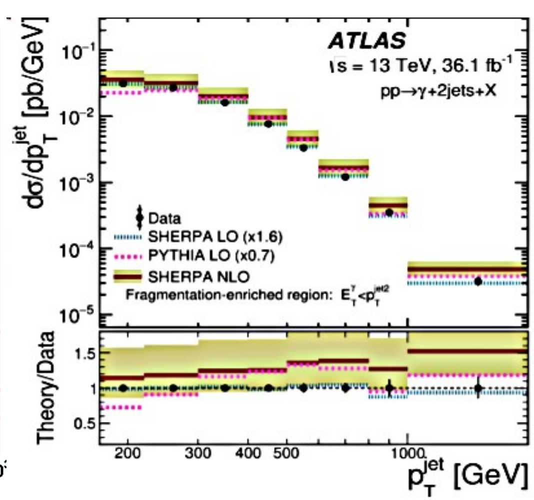
Multijet final-states (N_j>3) still challenging for multi-leg models:

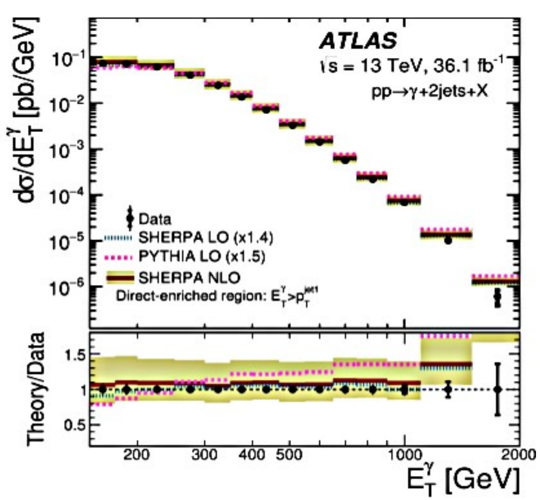


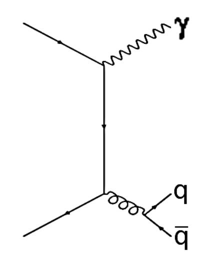
[P.Loch/ATLAS]

- Recent NLO multijet MC predictions improve data-theory agreement:









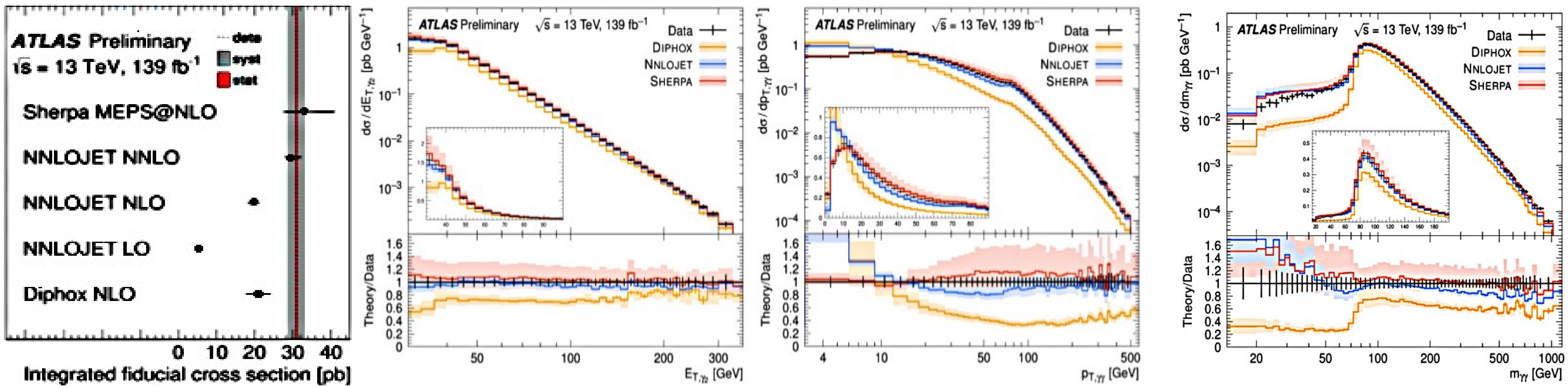
[S.A.Malik/ CMS]

[F.Siegert/ ATLAS]

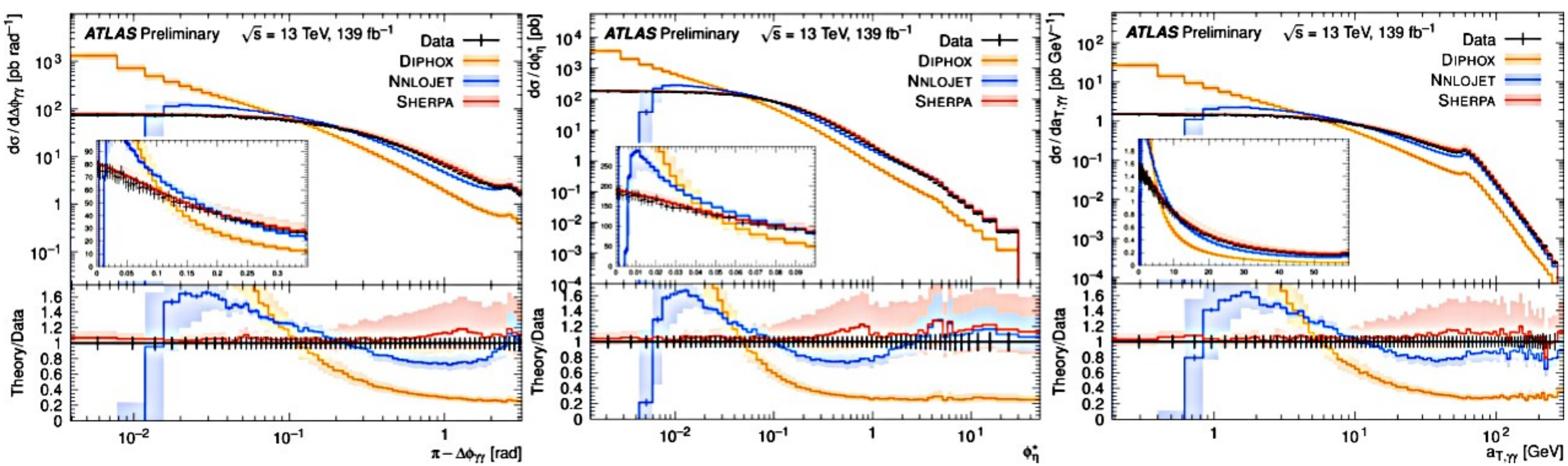
Data vs. pQCD at N^nLO: Diphotons

[F.Siegert/ATLAS]

- Multiple differential diphoton distributions: Excellent test-bed for **NNLO** & NLO+**multileg** MCs: Total rate well reproduced by NNLO, soft p_T by SHERPA:



- Regions at large φ decorrelation well modeled by NNLO, small φ by SHERPA:

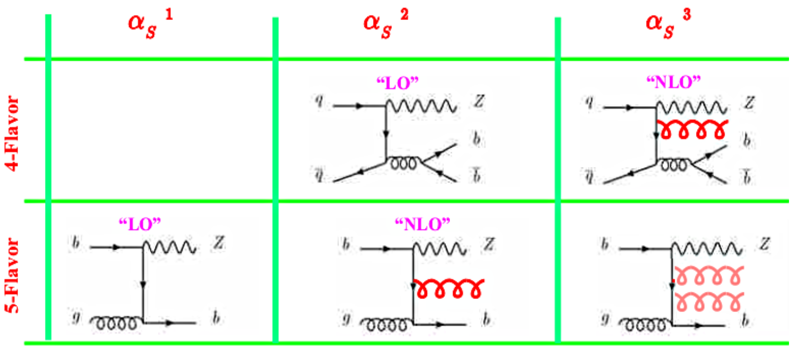


Data vs. pQCD at N^nLO: Z+b-jets

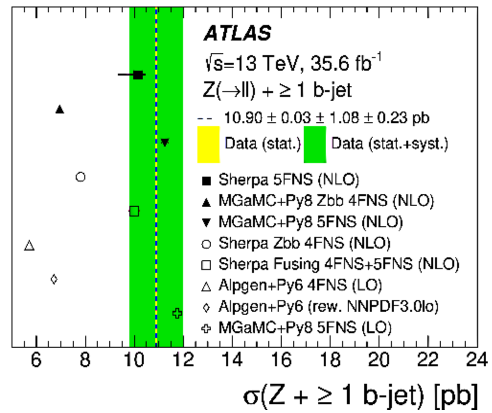
- Z+1,2 b-jets is an ideal channel to test 4-,5-flavour fix-order & **multi-leg** theory:

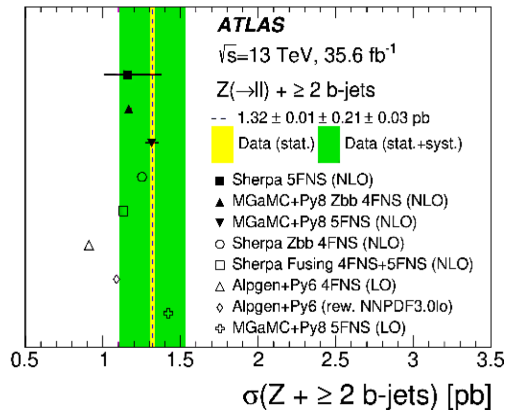
[S.Taheri]

Fred Olness's talk-U Manchester-22 April 2016



- data in the Z+ $\geq$ 1 b-jet and Z+ $\geq$ 2 b-jets cases are better described by 5FL prediction and 4FL prediction, respectively.

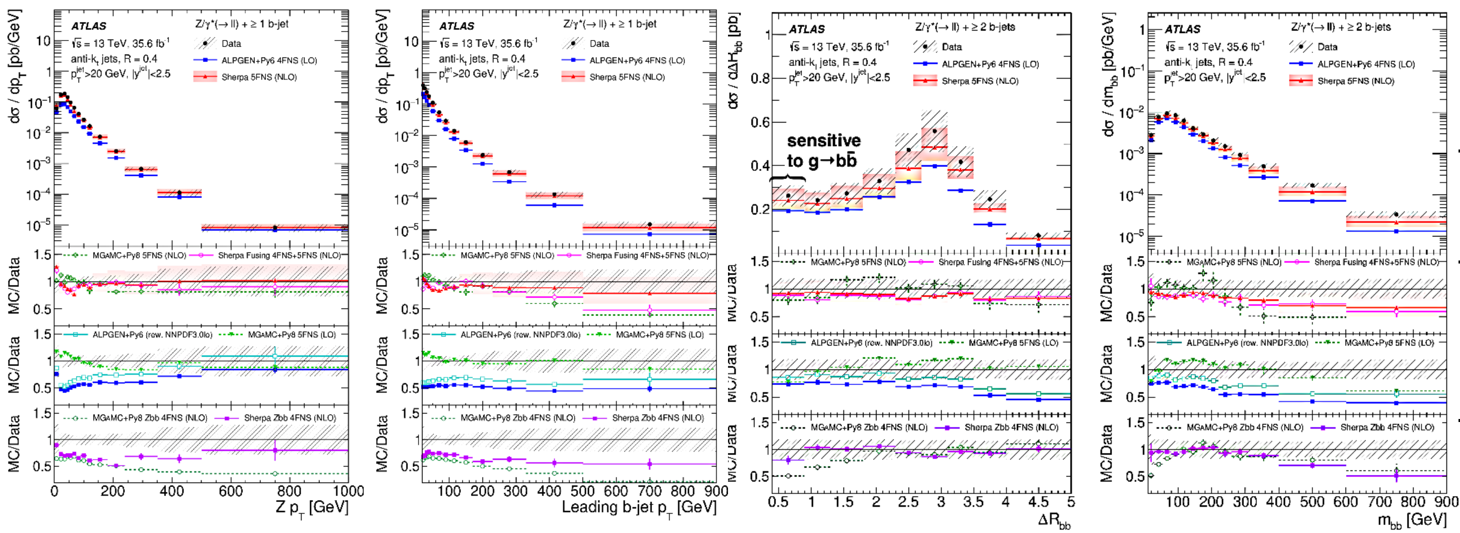




– NLO-5FNS SHERPA & MG5 describe well total x-section

– LO 4FNS MCs largely underestimate data.

- Multiple differential Z+1,2 b-jets distribs. to improve higher-order & multileg theory:



[C.Vittori/ATLAS]

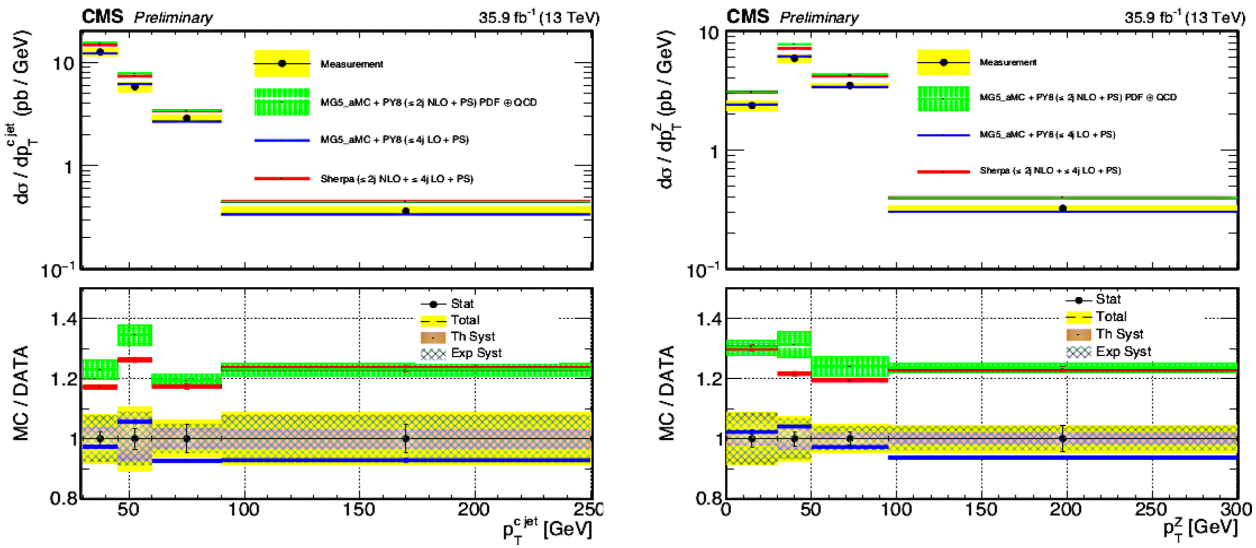
– NLO-5FNS SHERPA best.

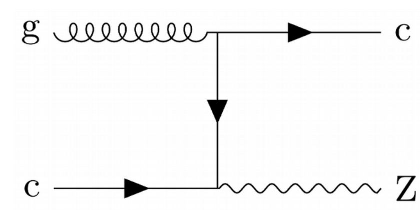
– 5FNS LO MG5+PY8 better than NLO (more legs in ME+PS)

– But all models underestimate large m(bb)

Data vs. pQCD at N^{n}LO: Z+c-jets, Z+b-jets

- Z+c-jets: MG5+PY8 (2j) OK, but MG5+PY8(4j) & SHERPA(4j) overestimate data.

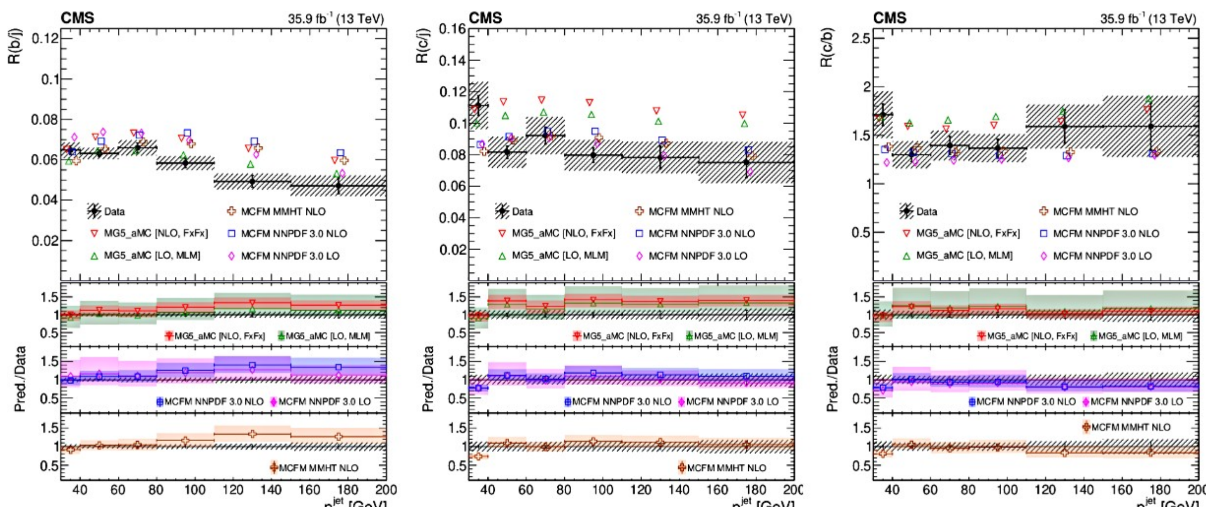


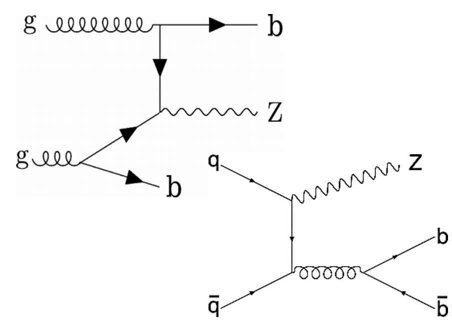


Additional constraints to charm PDF

[A.Stepennov/CMS]

- Z+b-jets spectra vs. theory: R(b/j) and R(c/j) under-estimated. R(c/b) OK.

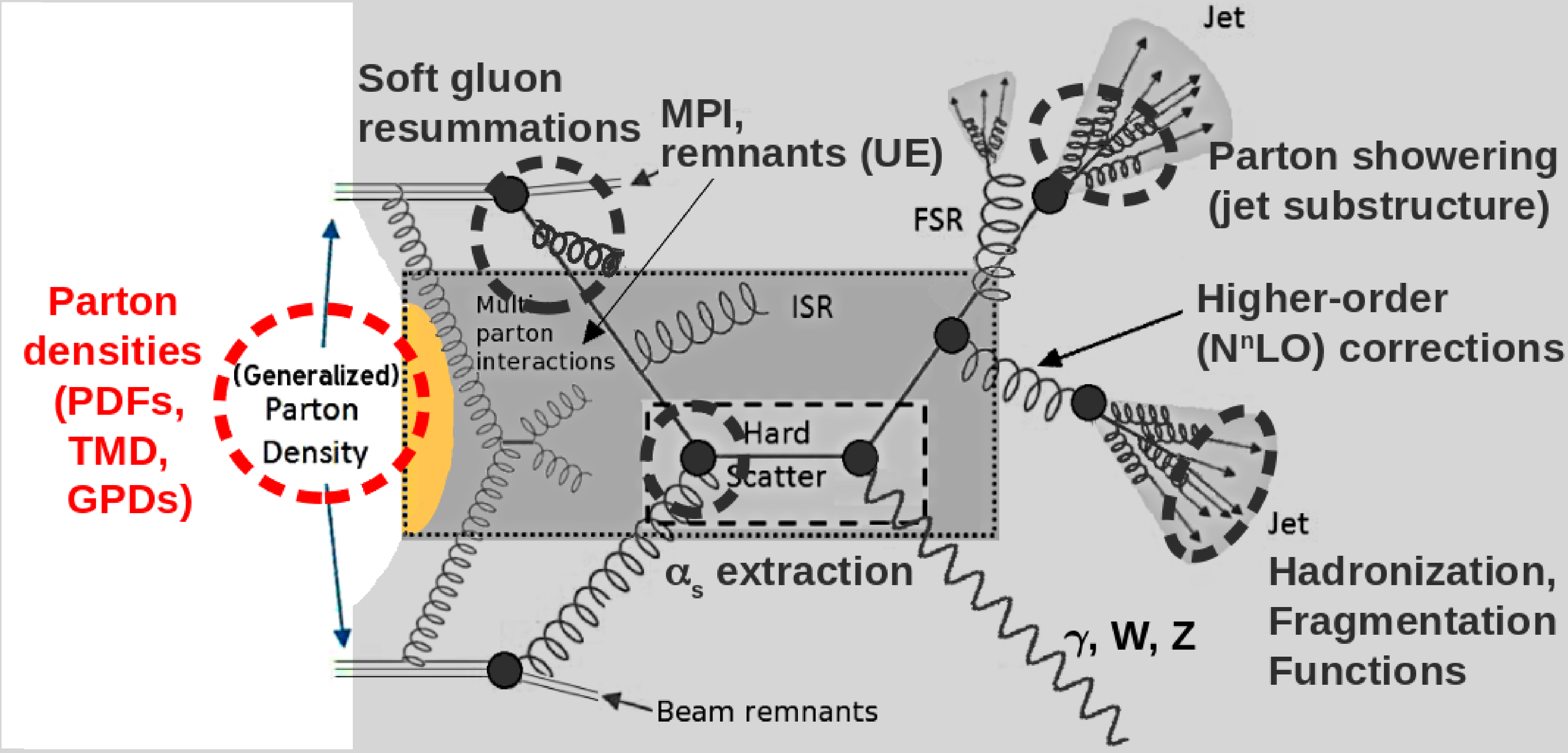




Additional constraints to b-quark PDF & multi-leg HF pQCD

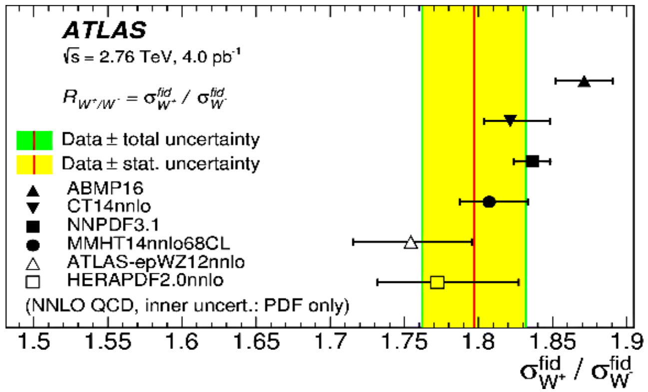
(3) Parton densities

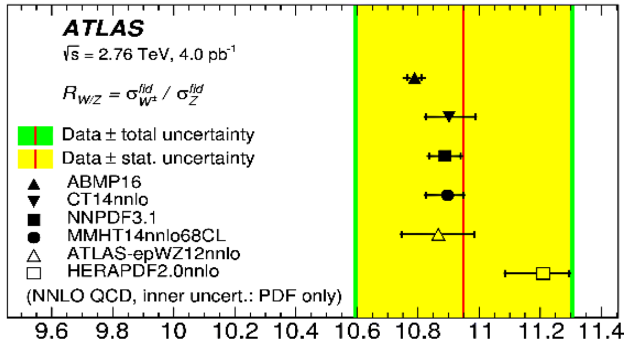
- Typical proton-proton collision at the LHC:



New PDF constraints at the LHC: Inclusive W, Z

- ATLAS W, Z data at 2.76 TeV vs NNLO PDFs:





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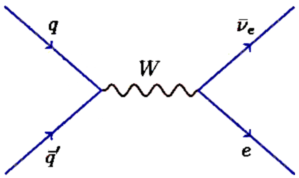
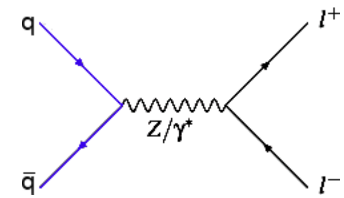
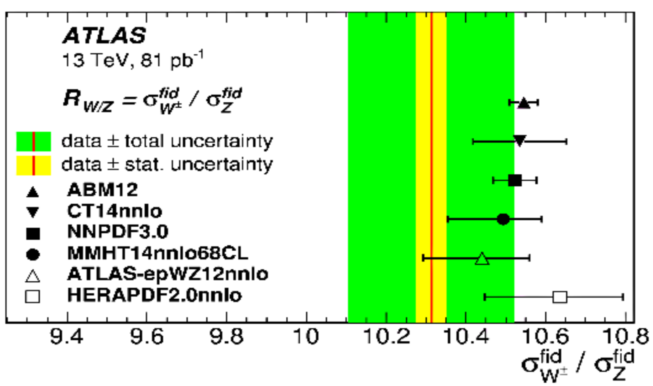
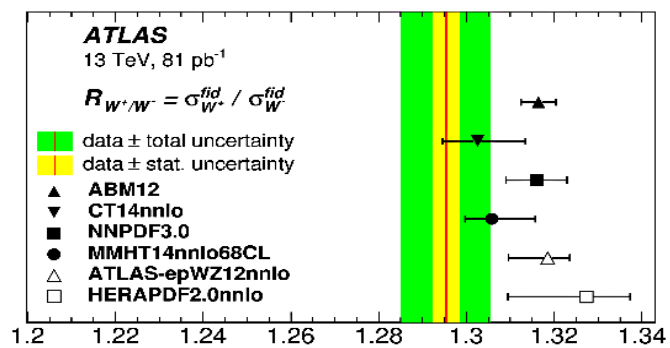




– W/Z ratio: Sensitive to strange quark PDFs.
– W^+/W^- ratio: ABMP16 PDF underestimates (<2σ) data.
HERAPDF2.0 a bit high & generally different from other PDFs.

- ATLAS W, Z data at 13 TeV vs NNLO PDFs: [K.Lohwasser/ATLAS]





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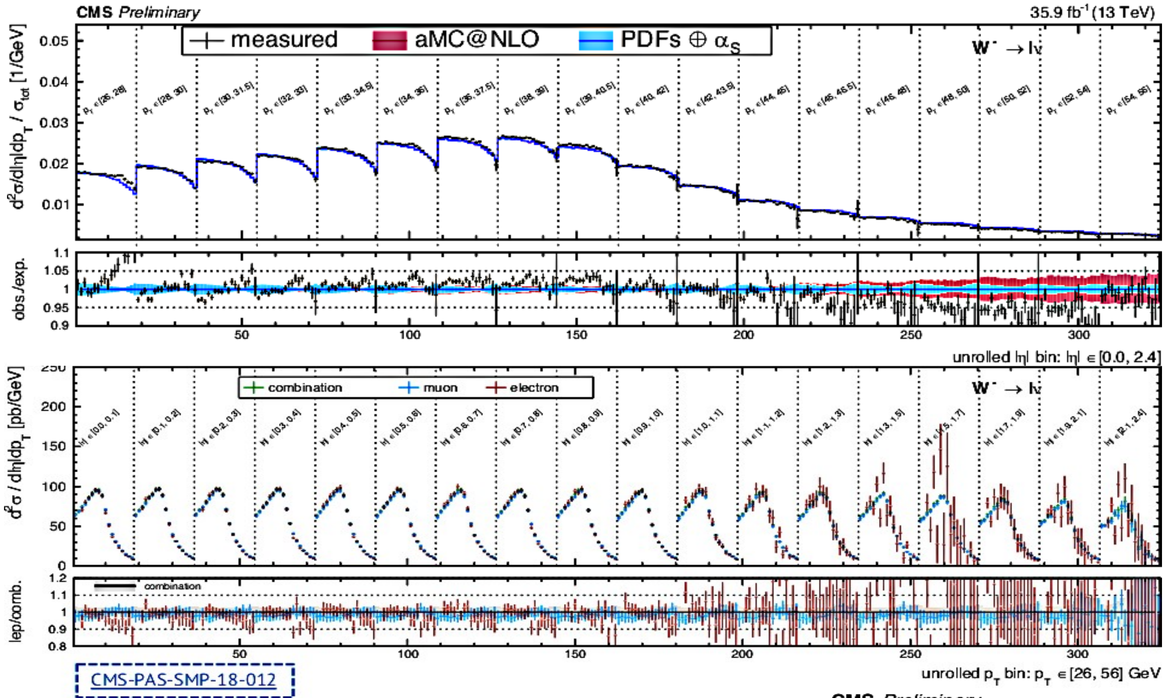
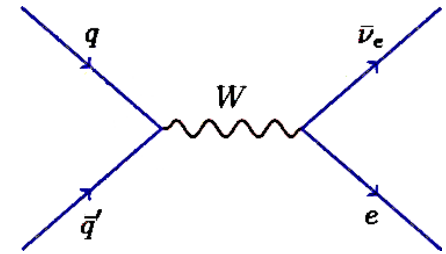
– W/Z ratio: Preference for enhanced strange-q content (not visible in 2.36 TeV data)
– W^+/W^- ratio: Data prefer smaller u/d valence ratio than predicted by most PDFs

New PDF constraints at the LHC: W (differential)

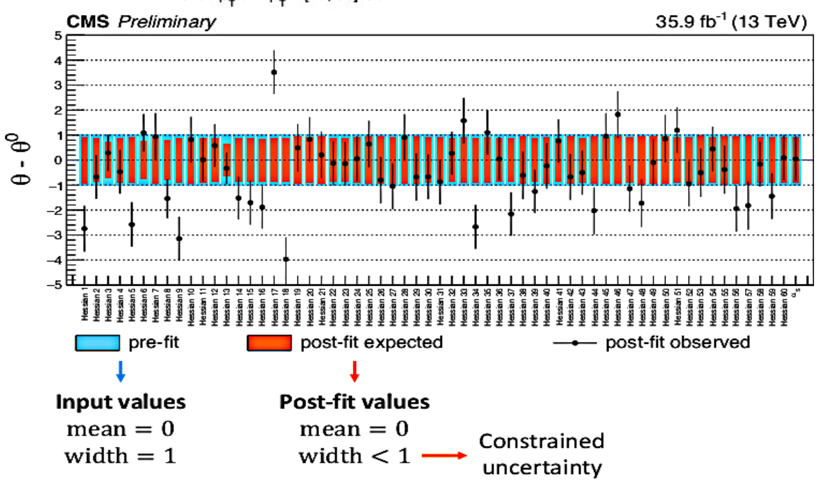
- High-precision double differential W p_T, η, helicity cross sections:





[R.Salvatico/CMS]

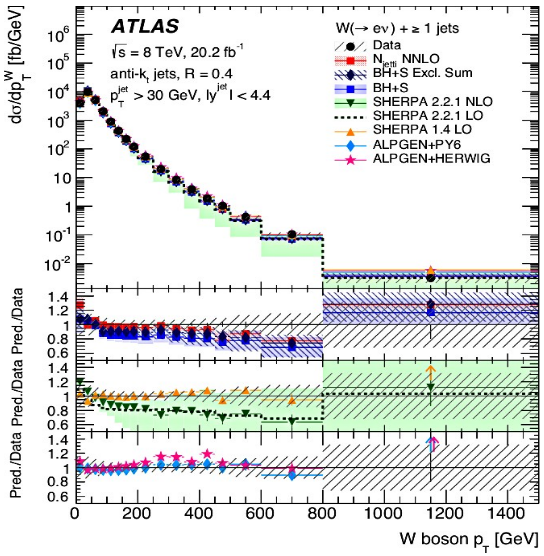
- Pulls & post-fit constraints on 60 Hessian NNPDF3.0 parton density sets:

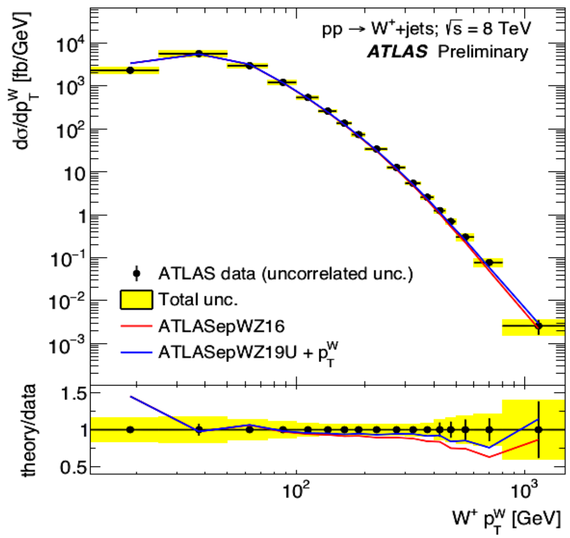


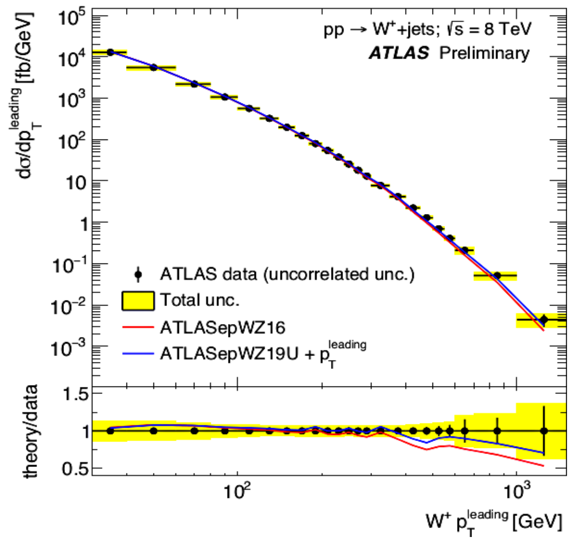
Impact: 10–30% improvements expected on NNPDF3.0 sets.

New PDF constraints at the LHC: W+jets

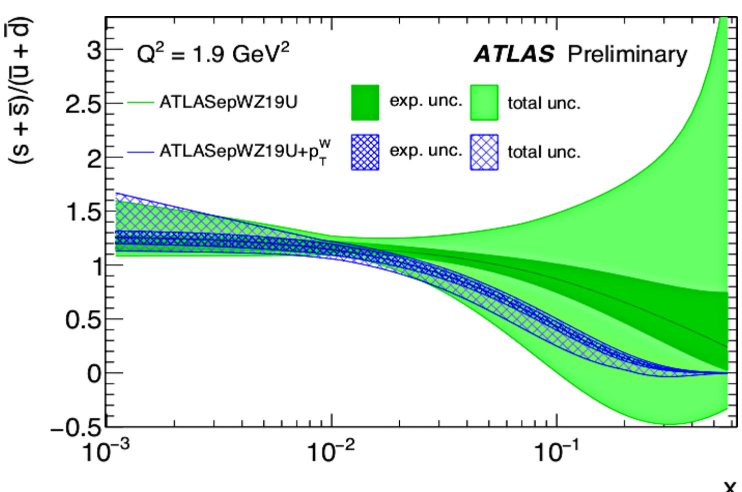
- ATLAS W+jets p_T spectrum added to new HERA+W,Z fit: **[M.Sutton/ATLAS]**



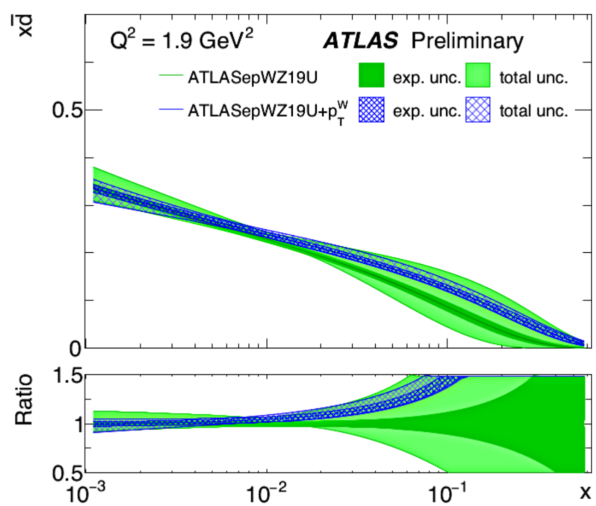


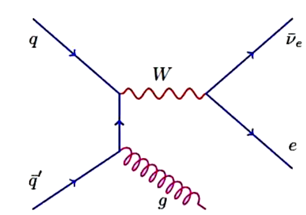


- Depleted s-quark PDF at large-x:



- Small changes in light-quark PDFs:

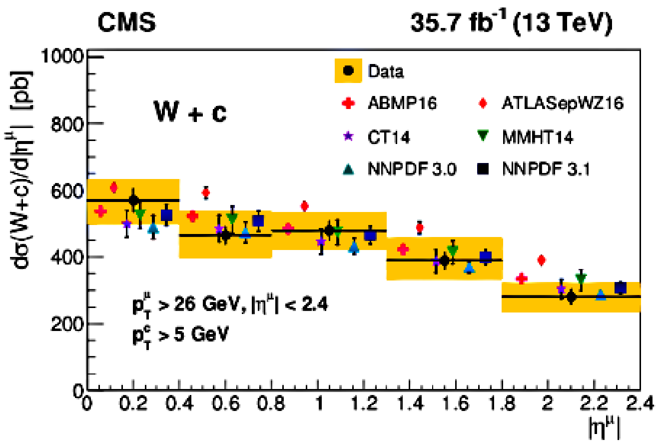


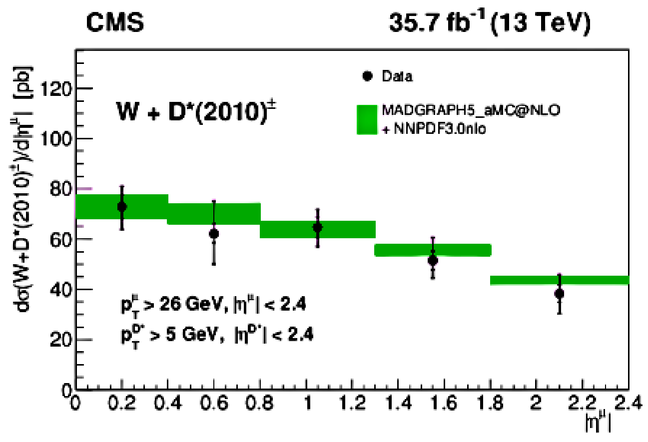


Harder dbar
Softer d-val.
Unchanged u-val.

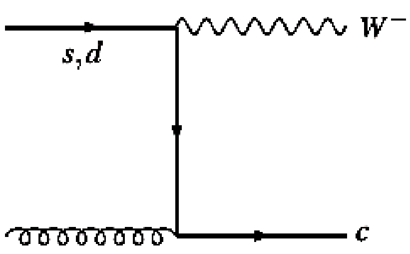
New PDF constraints at the LHC: W+charm

- Newer CMS W+charm data well reproduced by NLO predictions:



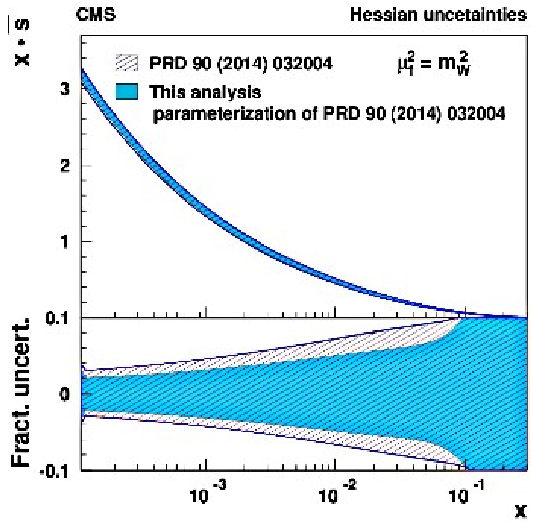


[A.Stepennov/CMS]

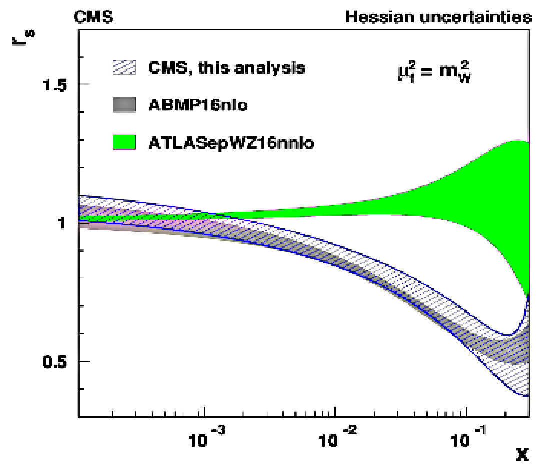


- Strange-quark PDF & strangeness suppression factor agree with ν-scatt. exps., disagree with previous ATLASepWZ16nnlo (central values):

strange quark distribution



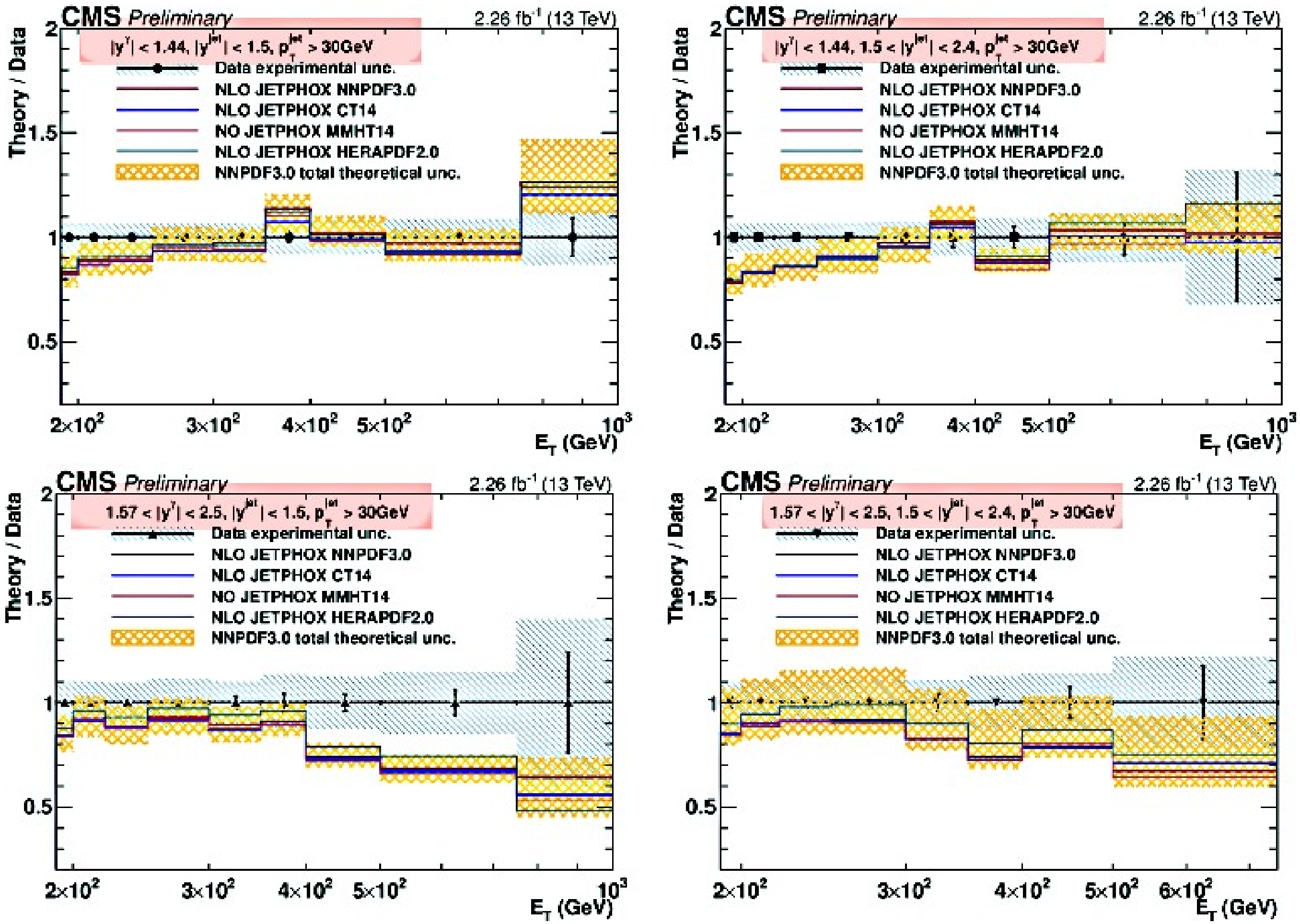
strangeness suppression factor



(Green band: ATLAS uncertainties only, missing parametrisation ones)

New PDF constraints at the LHC: γ+jet

- CMS photon+jet spectra compared to NLO pQCD with varying PDFs:

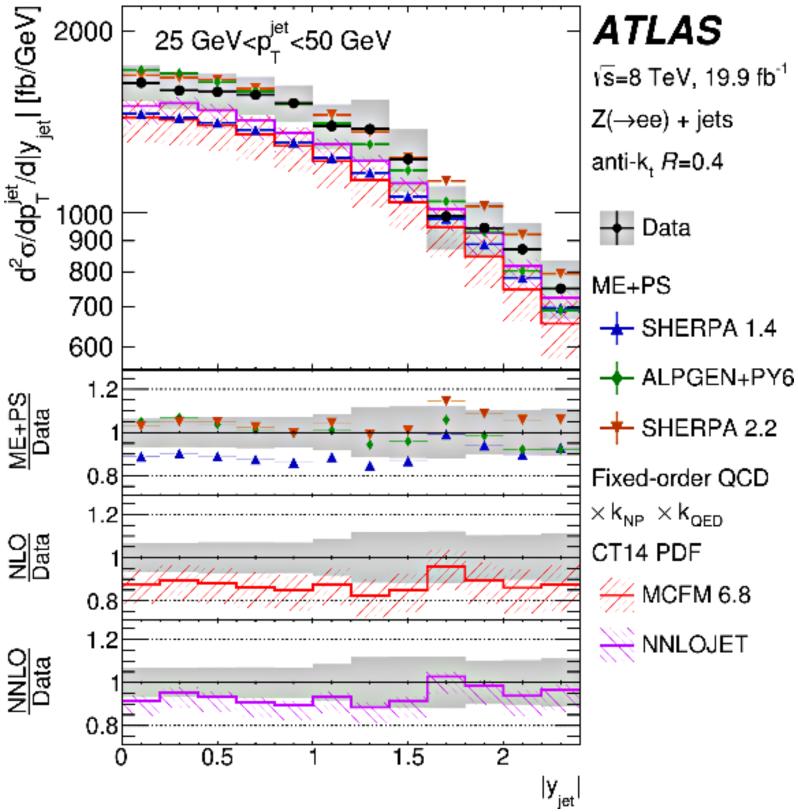


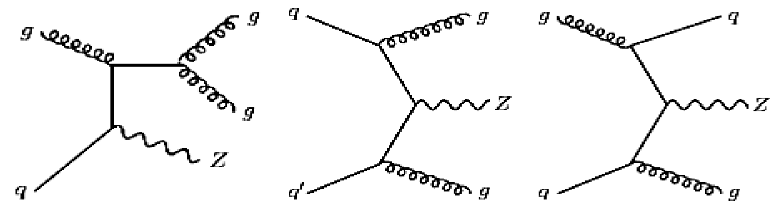
[S.A.Malik/ CMS]

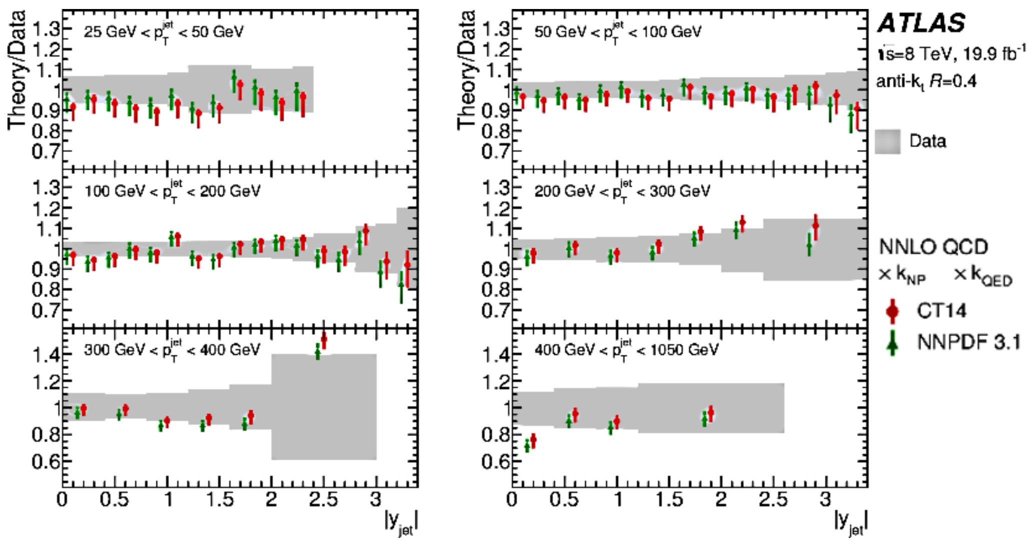
- Mild differences between PDFs within uncertainties. Better exploitation to provide extra input for global PDF fits with NNLO calculations.

New PDF constraints at the LHC: Z+jets

- Latest ATLAS Z+jets spectra reproduced by NLO ME+PS & NNLO:







NNLO NNPDF3.1 & CT14 PDFs show 2–5% differences

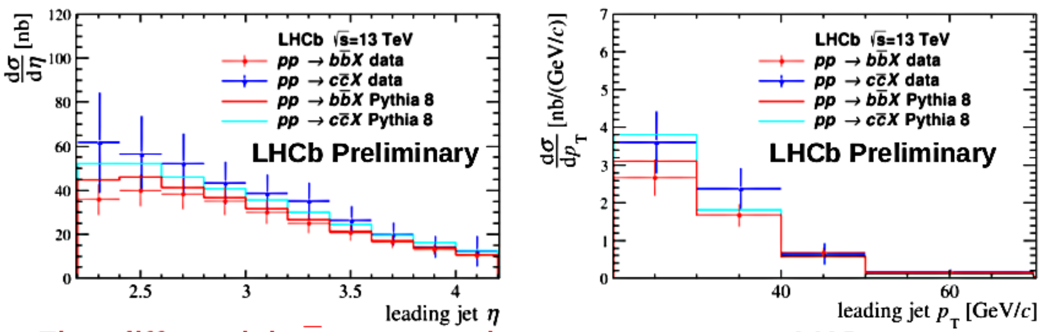
[C.Vittori/ATLAS]
[S.A.Malik/CMS]

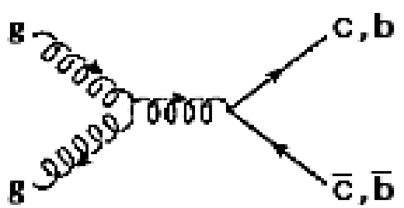
- Measurements exploitable to provide extra input for global PDF fits.

New PDF constraints at the LHC: c-,b-jets (fwd.)

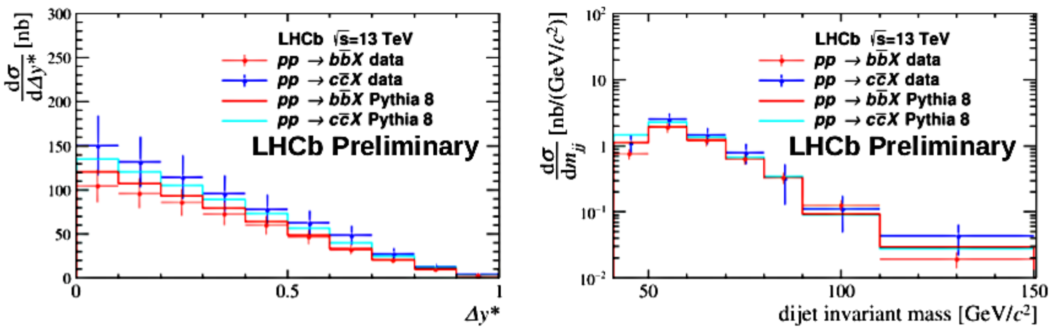
- Novel forward charm, bottom jet cross sections (improved 2D BDT fit to separate flavour composition). First time charm jets measured in forward direction:

[L.Sestini/LHCb]

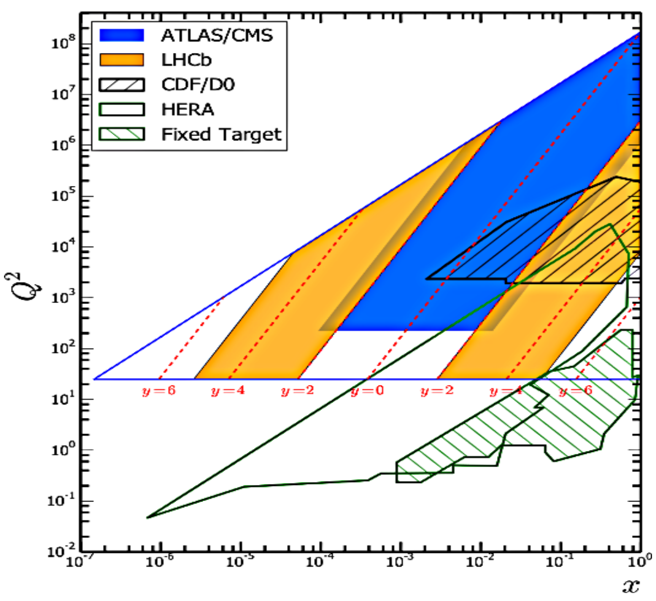




First differential $c\bar{c}$ cross section measurement at LHC



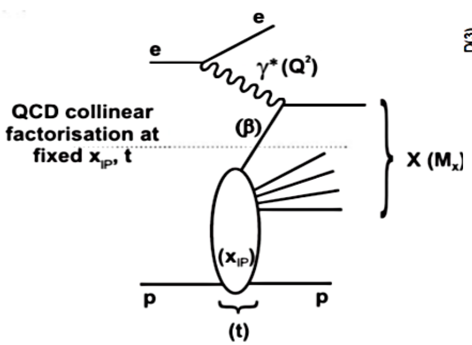
- Unique novel constraints of low-x & high-x gluon PDF phase space covered by LHCb:

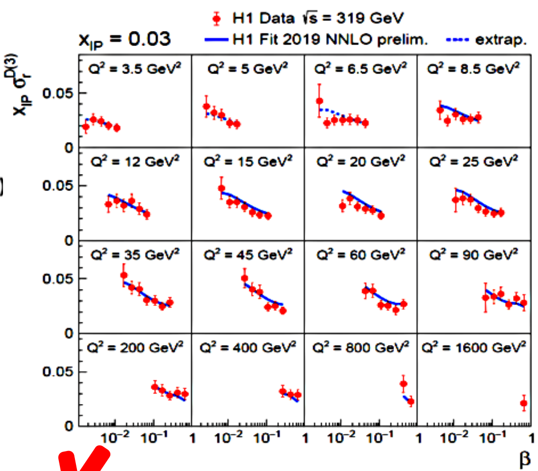


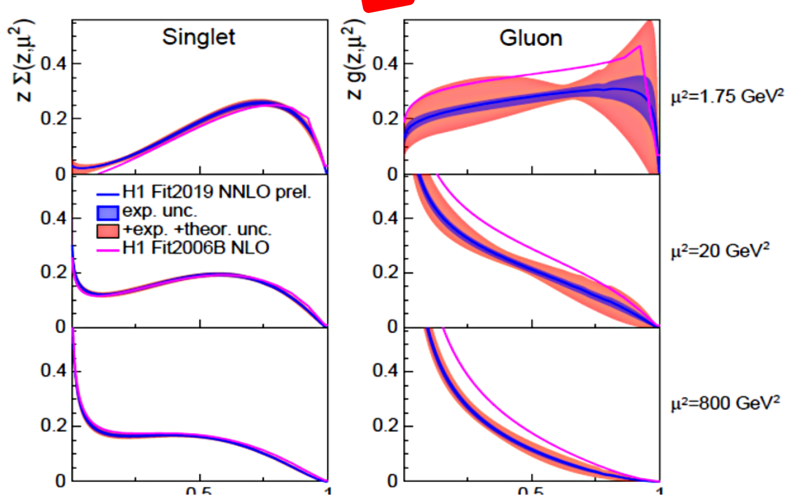
(Incorporation into global PDF fits will need NNLO calculations for charm, bottom x-sections)

Improved diffractive PDFs at HERA

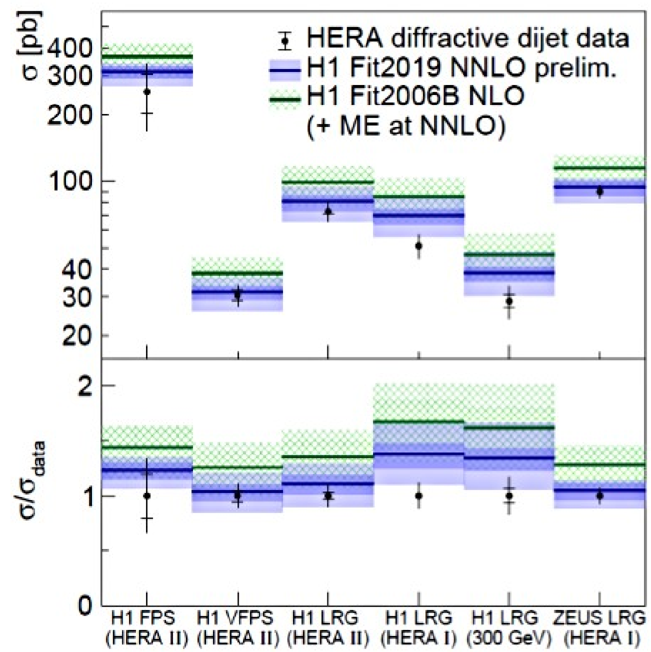
- New global H1 inclusive diffractive DIS fit at **NNLO**: **[A.Sarkar/H1&ZEUS]**







But the fit can also be used to predict cross sections for diffractive jet production which are not inputs to the fit

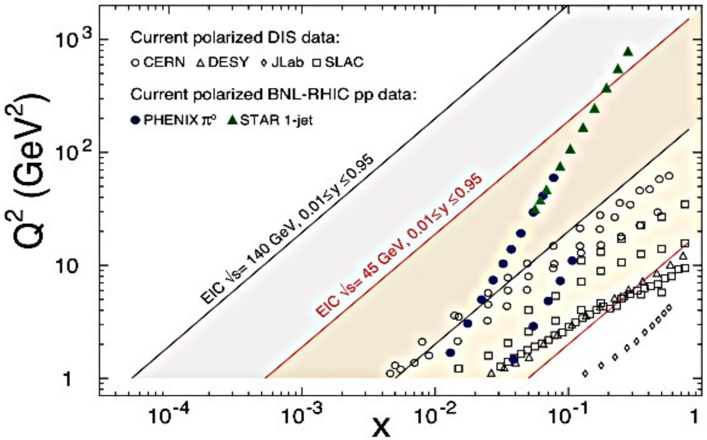


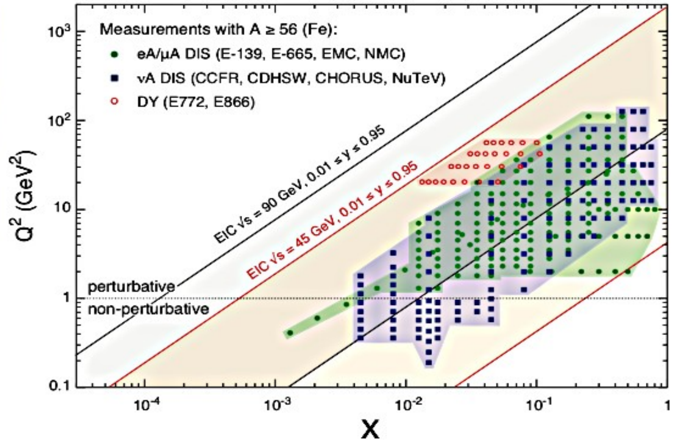
The NLO PDF overpredicts these cross sections

- Gluon diffractive PDF reduced by ~25% compared to previous NLO result. Better agreement with diffractive dijet data.

Parton densities (future)

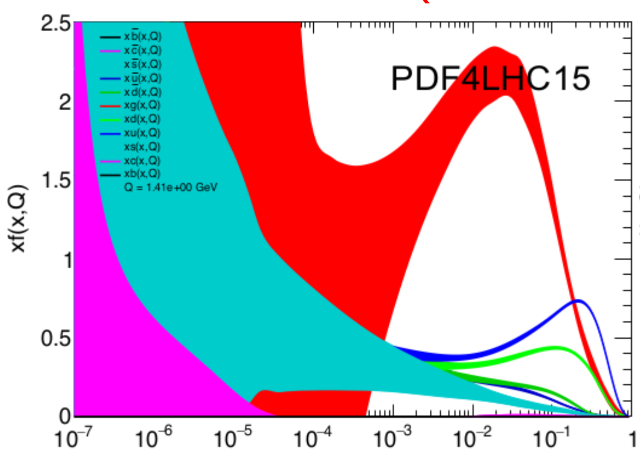
- EIC: Unique machine: World 1^{st} polarized e-p,A collider. World 1^{st} e-A collider

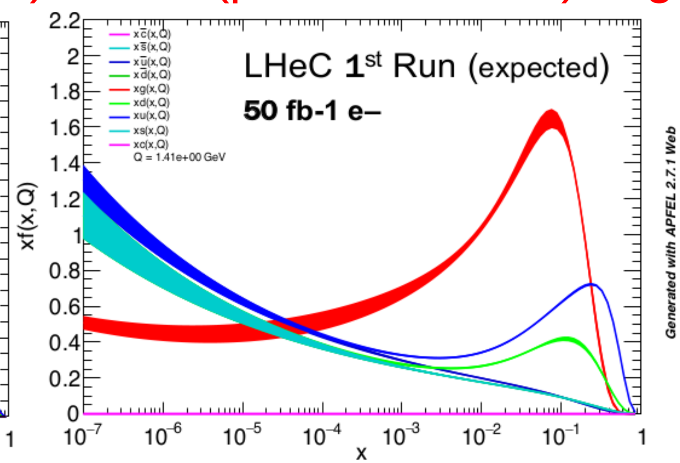




[S.Joosten/ EIC]

- LHeC: Ultimate low-x (saturation), mid-x (precision EWK), high-x (BSM) PDFs





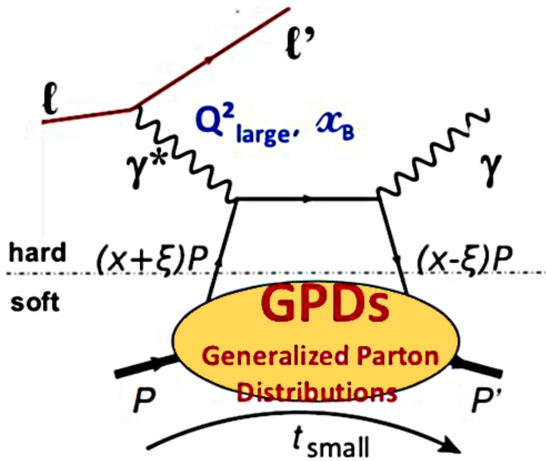
[C.Gwenlan/ LHeC]

situation today → after 1^{st} LHeC Run

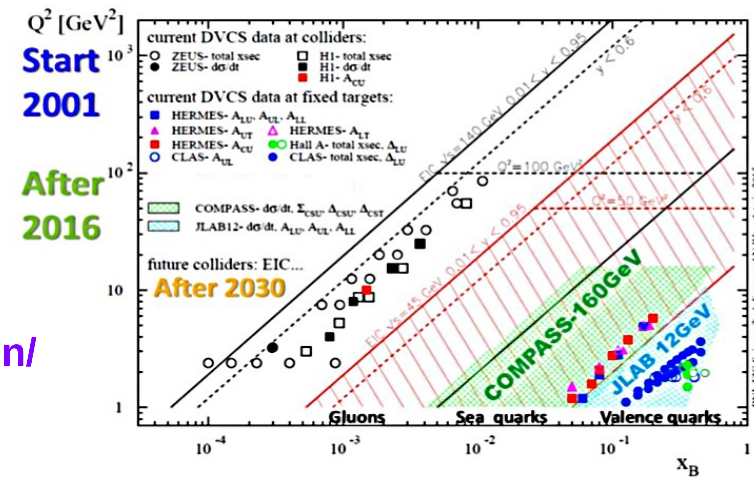
with further improvements after full running period, plus HQs, (DIS jets, …)

Generalized parton densities (future)

- COMPASS: Deeply Virtual Compton Scattering (DVCS): $l + p \rightarrow l' + p' + \gamma$

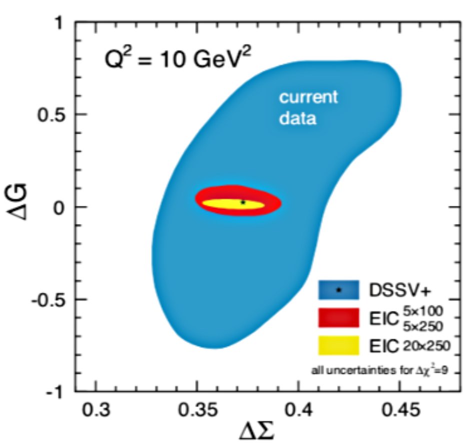


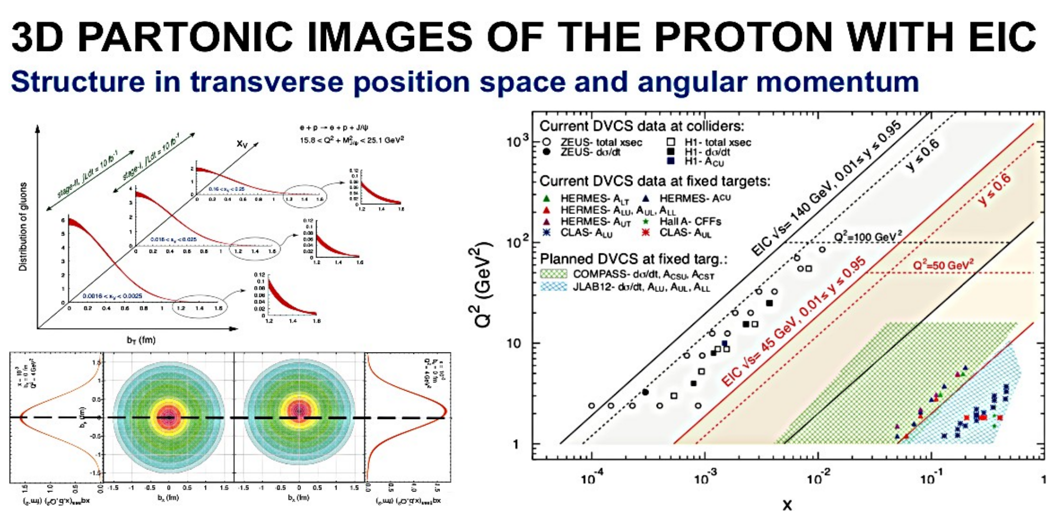
[M.Meyer, PJ.Lin/ COMPASS]



- EIC: Precise study of 3-D & polarization structure of sea-quark & gluons

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

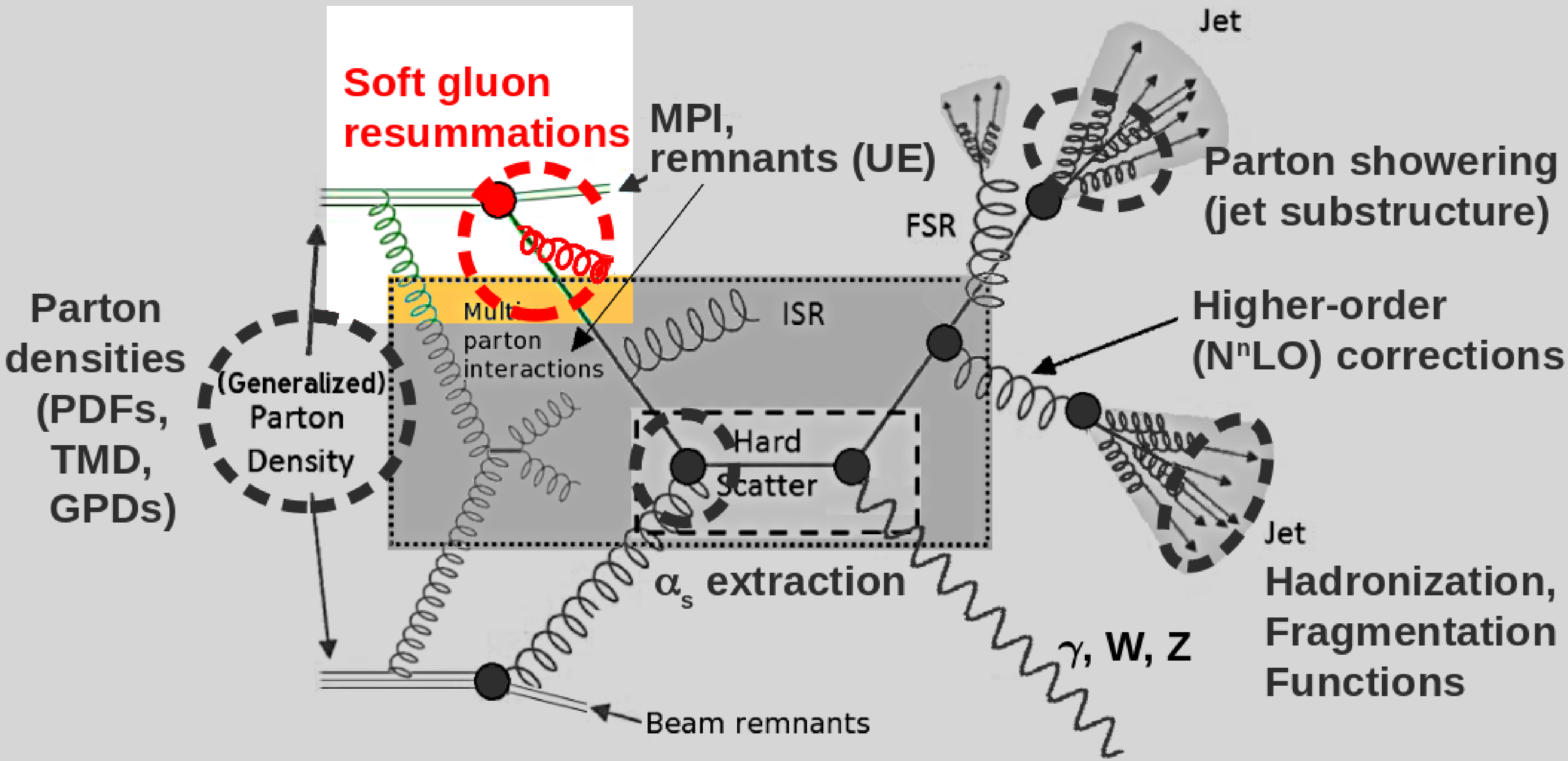




[S.Joosten/EIC]

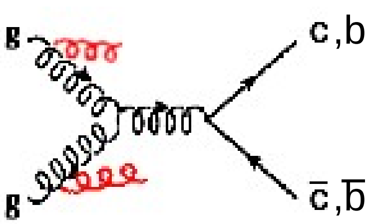
(4) Higher-order log resummations

- Typical proton-proton collision at the LHC:

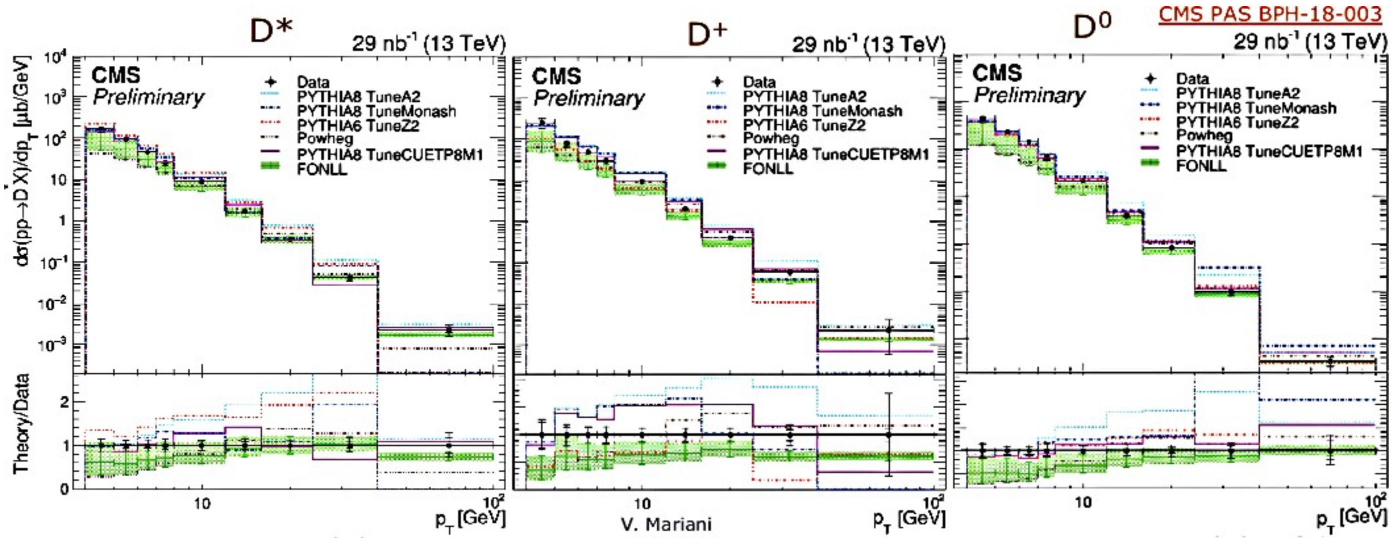


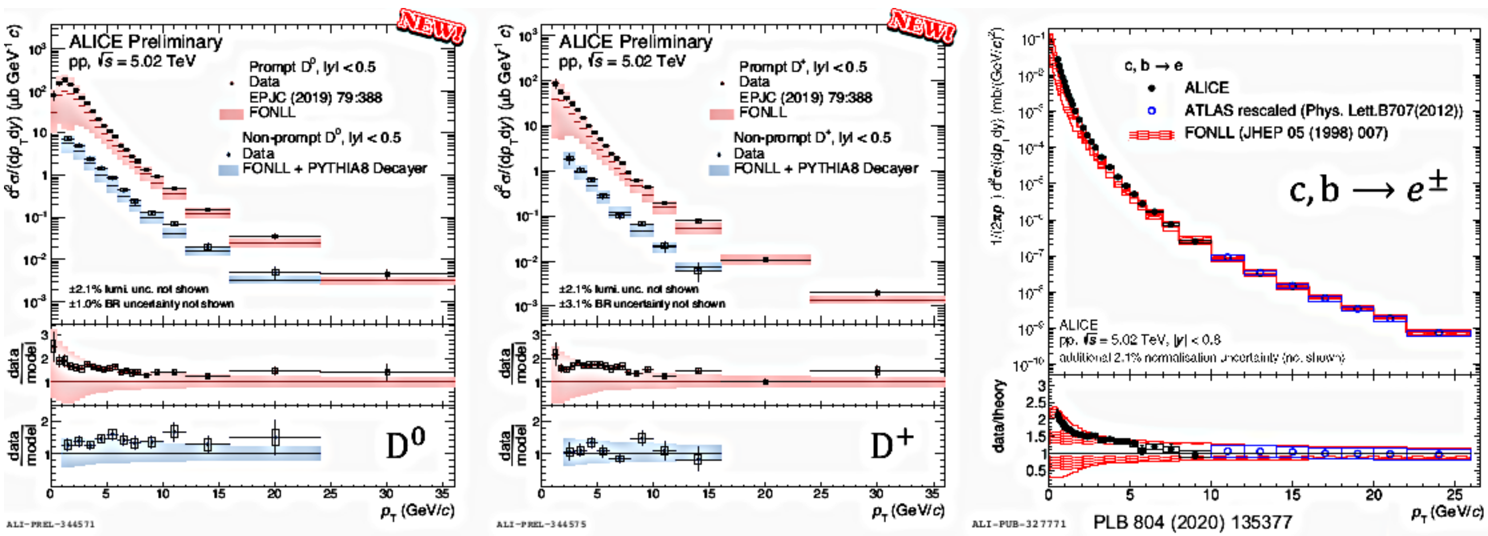
Logs resummation: Low-p_T charm, bottom

- Soft charm & bottom data consistent with but systematically above FONLL predictions (missing NNLL terms?):



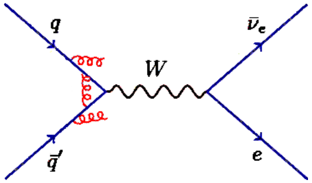
[V.Mariani/CMS]



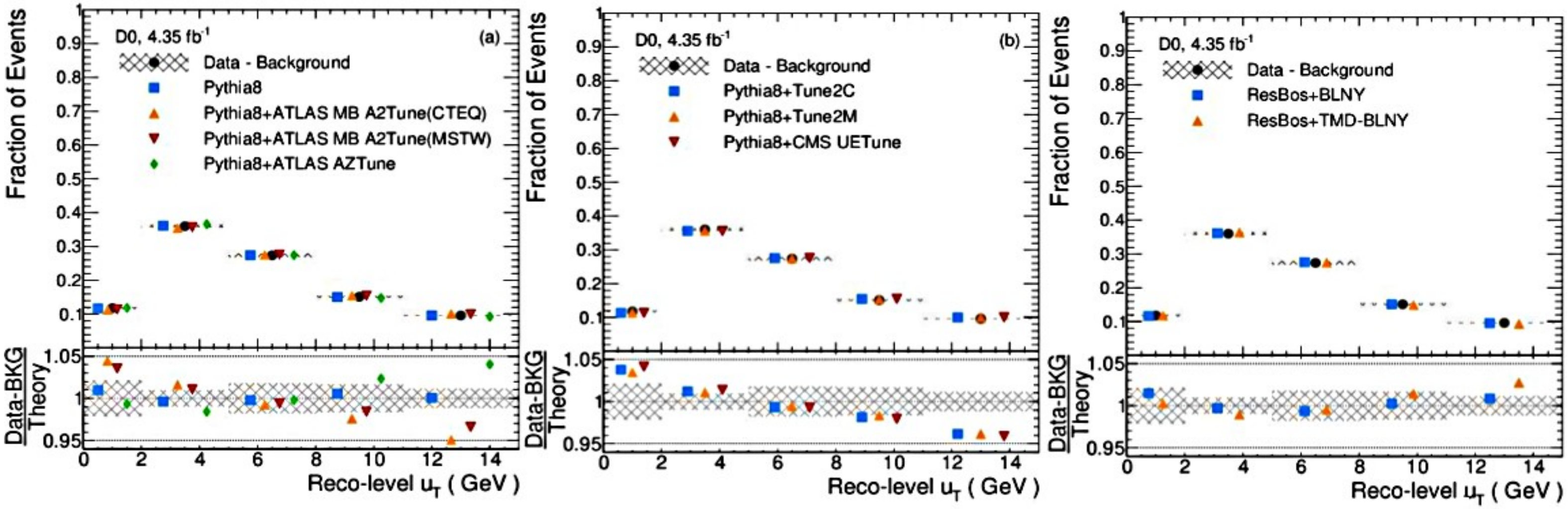


[L.Vermunt/ ALICE]

Logs resummation: Low-p_T W spectra



- Low-p_T W from precise hadronic recoil measurement (normalized recoil accurately calibrated with soft Z bosons):



- Constraints of theoretical models (resummation & PS MCs): **[C.Wang/D0]**

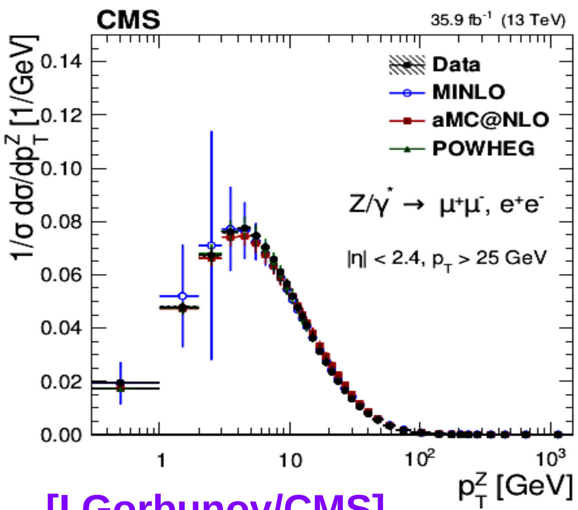
– ResBos+BLNY within 2% of data
– PYTHIA8 default tune: Good.
– PYTHIA8 tunes excluded: ATLAS MB A2Tune+CTEQ6L1, CMS UE Tune CUETP8S1-CTEQ6L1. Other tunes unfavoured.

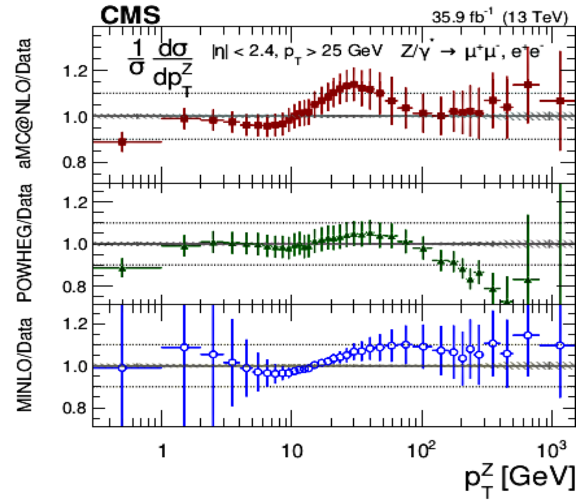
Generator/Model	χ^2/ndf	p-value	Signif.
RESBOS (Version CP 020811)+BLNY+CTEQ6.6	0.49	7.41×10^{-1}	0.33
RESBOS (Version CP 112216)+TMD-BLNY+CT14HERA2NNLO	3.13	1.39×10^{-2}	2.46
PYTHIA 8+CT14HERA2NNLO	0.32	8.63×10^{-1}	0.17
PYTHIA 8+ATLAS MB A2Tune+CTEQ6L1	12.25	5.84×10^{-10}	6.19
PYTHIA 8+ATLAS MB A2Tune+MSTW2008LO	6.17	5.83×10^{-5}	4.02
PYTHIA 8+ATLAS AZTune+CT14HERA2NNLO	6.61	2.60×10^{-5}	4.21
PYTHIA 8+Tune2C+CTEQ6L1	7.66	3.61×10^{-6}	4.63
PYTHIA 8+Tune2M+MRSTLO	7.32	6.89×10^{-6}	4.50
PYTHIA 8+CMS UE Tune CUETP8S1-CTEQ6L1+CTEQ6L1	8.80	4.23×10^{-7}	5.06

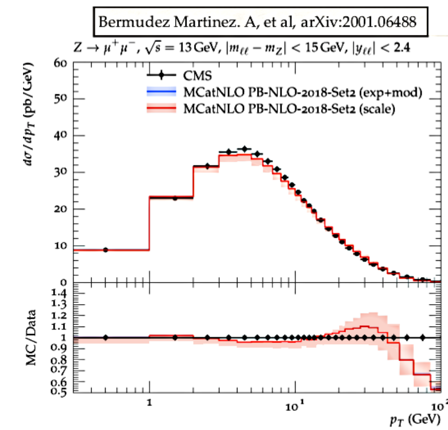
Important ingredient for W mass extractions!

Logs resummation: Low-p_T DY spectra

- Soft Z spectrum: Clean benchmark for all calculations (NLO+PS, NLO+TMD):

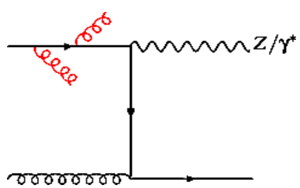


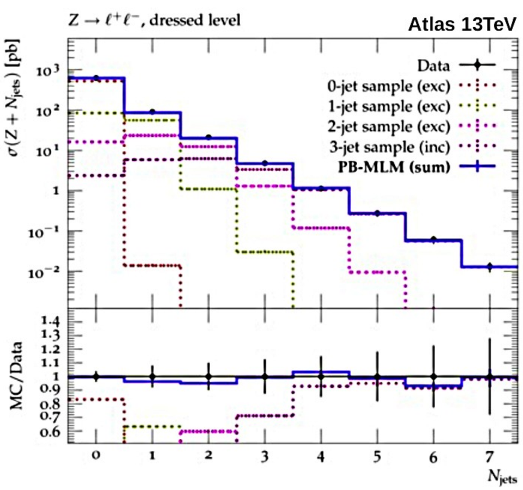


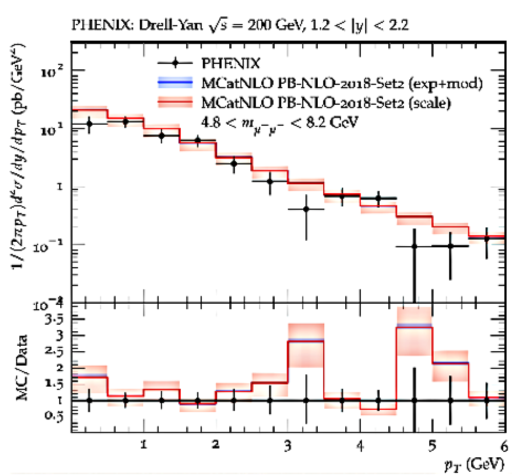


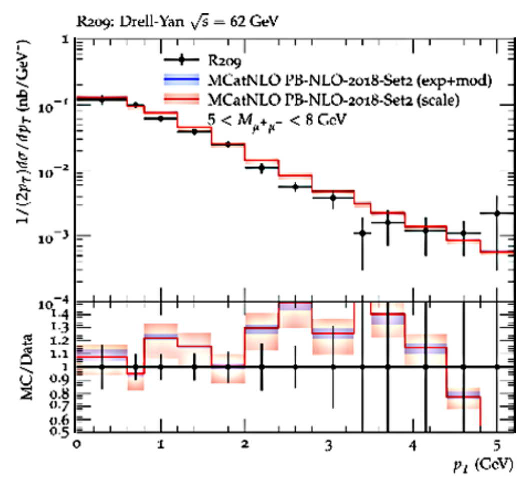
[I.Gorbunov/CMS]

- TMD-based approaches reproduce well Z+N-jets & low-$\sqrt{s}$ DY:





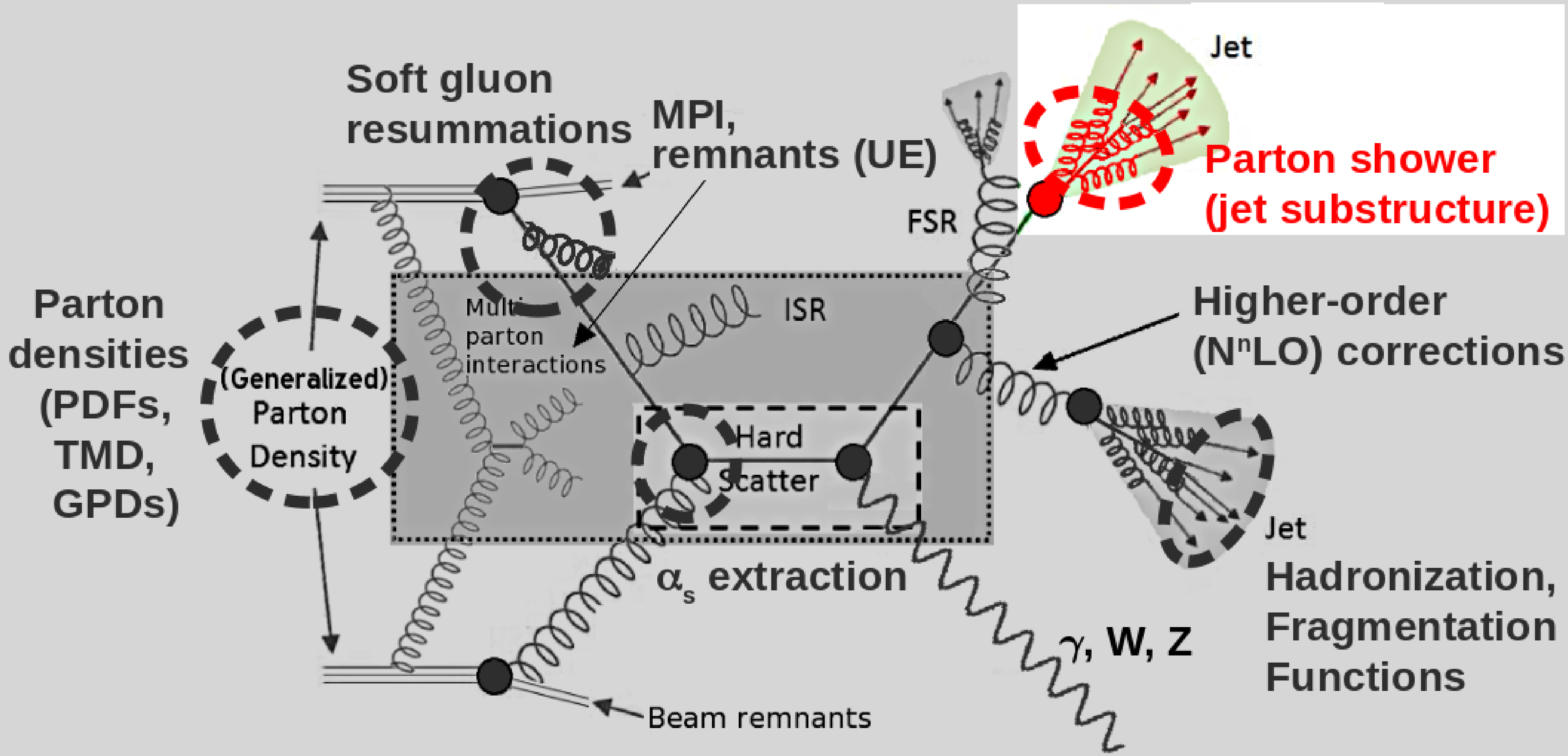




[A.Bermudez/S.Taheri/Q.Wang]

(5) Parton shower & jet substructure

- Typical proton-proton collision at the LHC:



Parton shower dynamics (Lund plane)

- Advanced studies of energy-angle (sub)emissions within jet, opened up with modern jet substructure techniques, allow to precisely probe PS [J.Roloff/ATLAS]

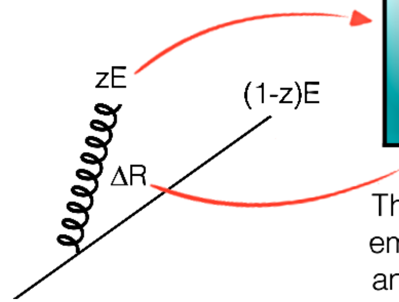
  Multiple applications beyond QCD:
  – g/q/Q discrimination
  – Boosted objects
  – (B)SM resonance jj decays
  – Pileup removal, ...

A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon

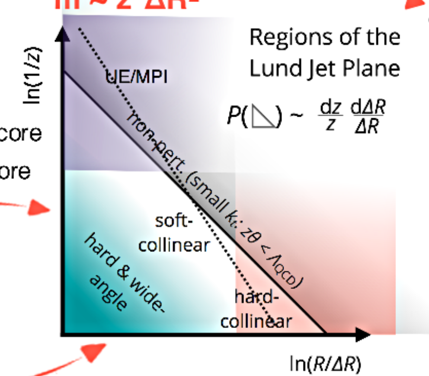
Emissions may be characterized by

z = relative momentum of emission wrt jet core

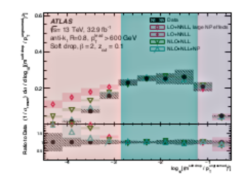
ΔR = angle of emission relative to the jet core



$m \sim z^*\Delta R^2$

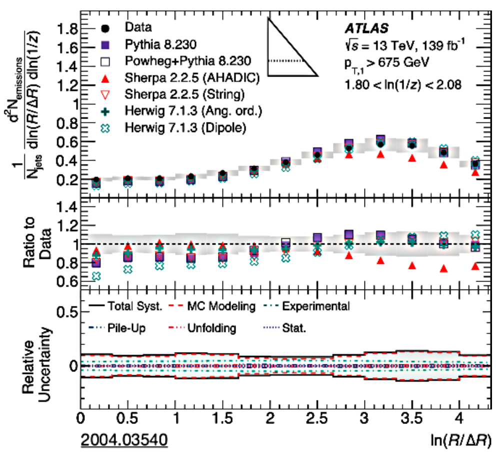


The jet mass is just one diagonal line in this space

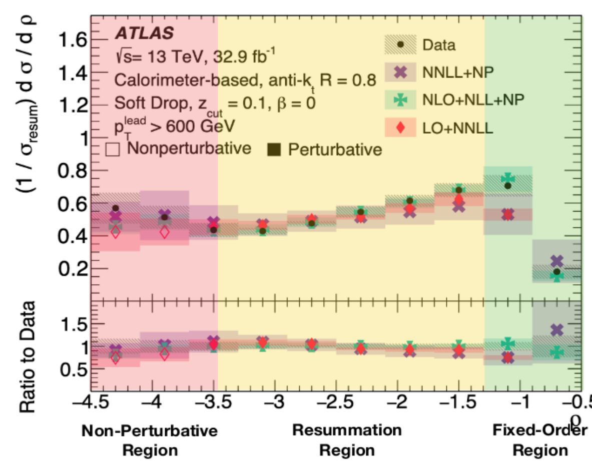


The Lund Plane is the phase space of these emissions: it naturally factorises perturbative and non-perturbative effects, UE/MPI, etc.

- Different projections/combinations of Lund plane vars. provide accurate PS info in various regimes (fixed-order, resumm., npQCD): ln(1/z), ln(R), jet mass,...



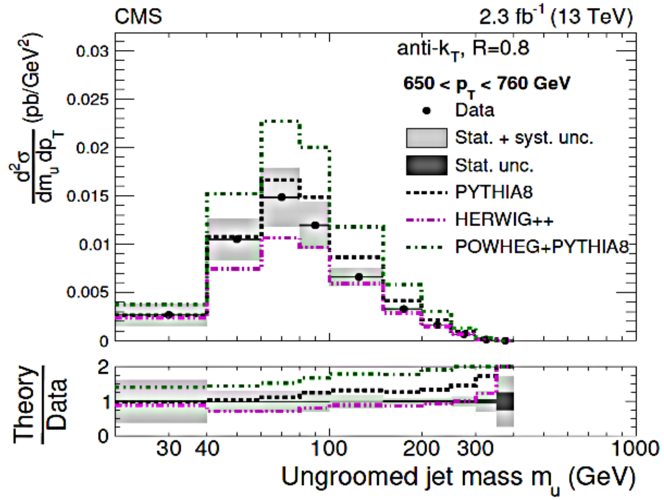
Critical for improving analytic calculations (NLO+NLL today) & MC PS models (in particular for badly known gluon jets).

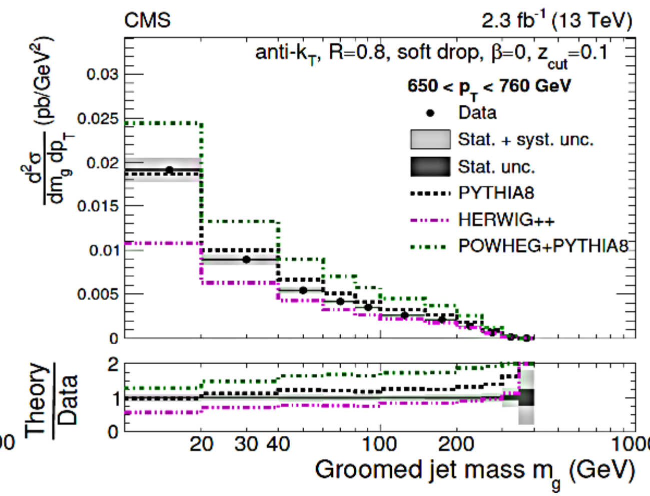


Jet substructure: Dijet & ttbar events

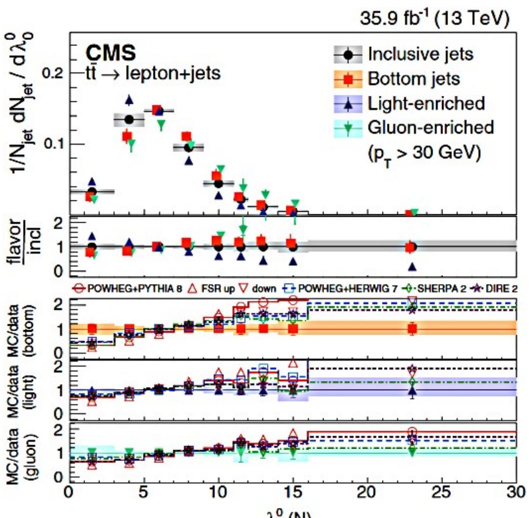
- Ungroomed vs. groomed jet mass in dijet events: **[D.Sunar-Cerci/CMS]**

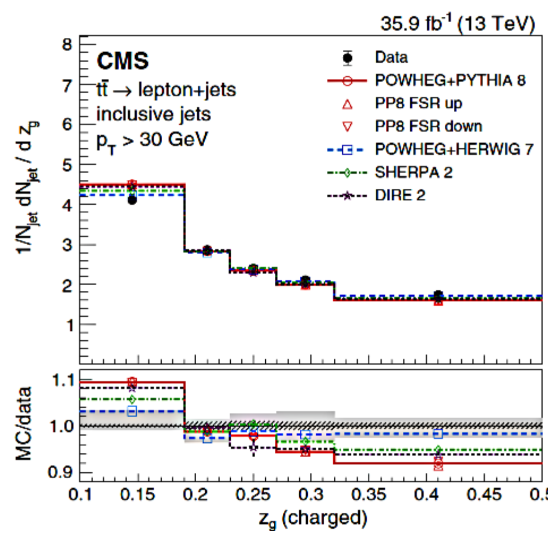
- Grooming depletes jet mass & suppresses Sudakov peak.
- Reduced exp. uncertainties by removing contamination from soft particles & pileup.
- PY8 alone better than POWHEG+PY8 & HERWIG++

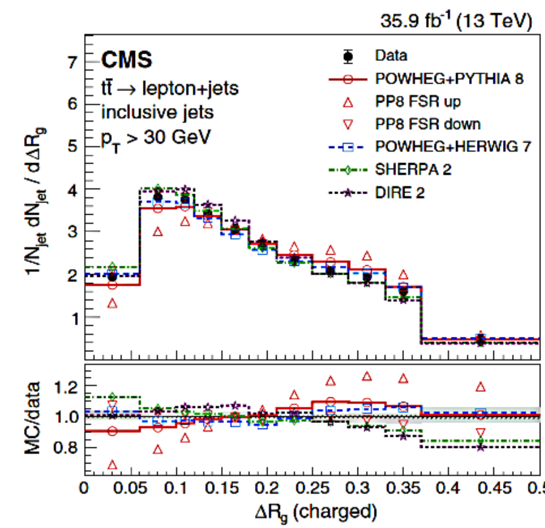




- Jets in top pair evts studied via gen. angularities, groomed momentum fraction, N-subjett. ratios,.. 10–50% data-TH diffs.: PS MC & analytic improvements needed







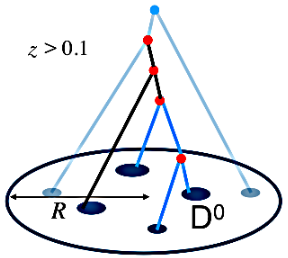
Jet substructure: charm jets, dead cone

- Jet grooming applied to study inclusive & charm-tagged jet substructure:

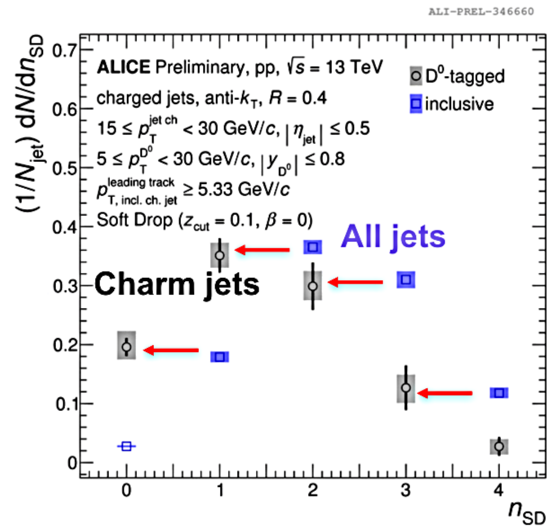
Jet grooming techniques used to count the number of hard splittings in jet fragmentation

N_{sd} = # splittings with > 10% p_T radiation

$$z = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \quad z > 0.1$$



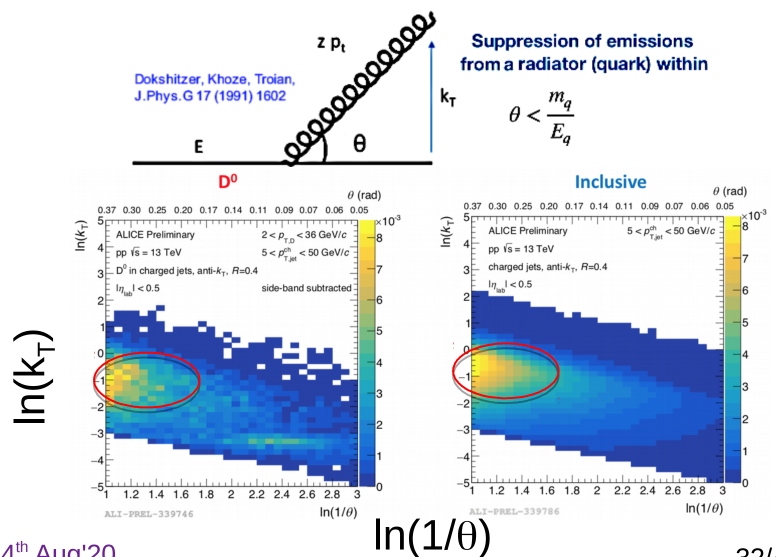
Charm jets have less hard splittings than inclusive jets

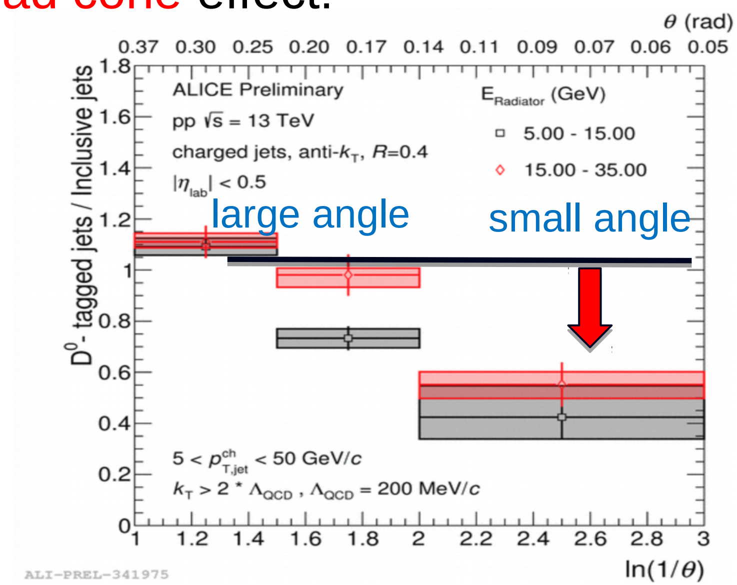


[L.Cunqueiro, J.Mulligan/ ALICE]

Harder fragmentation of heavy-quarks compared to light-q & gluons.

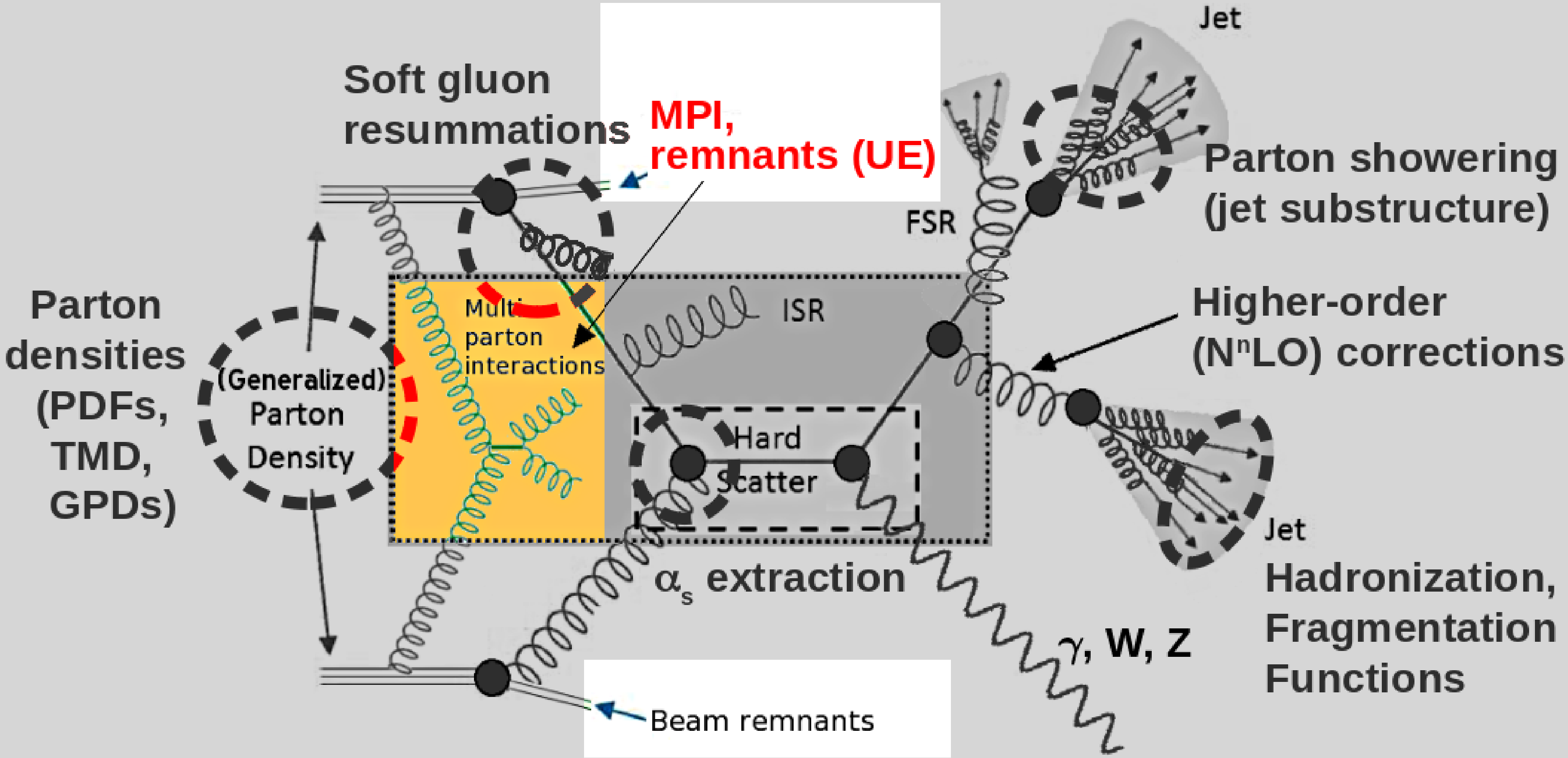
- 1st direct observation of heavy-quark dead cone effect!





(6) Multiparton interactions, UE, diffraction

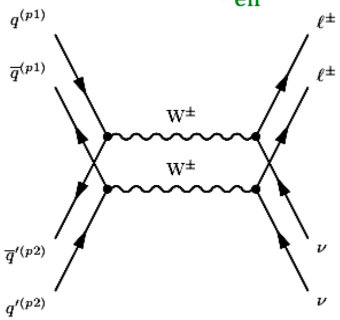
- Typical proton-proton collision at the LHC:



Double Parton Scattering: First evidence of ssWW

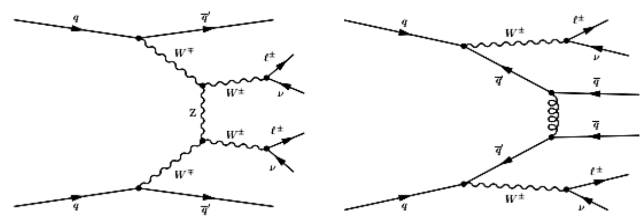
- Same-sign WW: Very rare, but historically considered DPS "smoking gun":

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$



DPS $W^{\pm} W^{\pm} \to \ell^{\pm}\nu\ \ell^{\pm}\nu$ is very promising

σ_A, σ_B = single hard scattering (SHS) cross sections

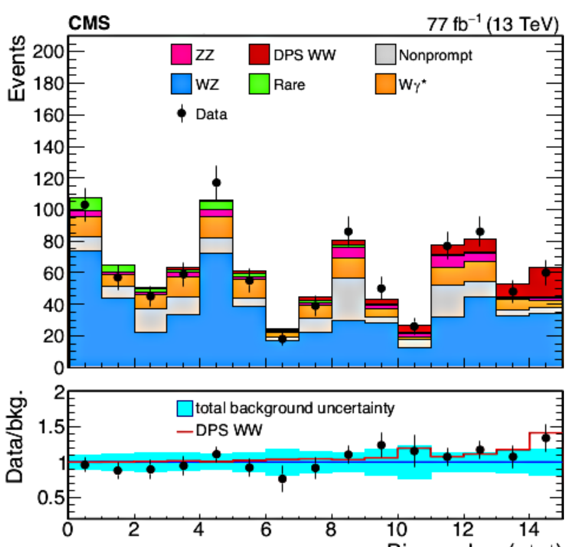


$n = 1$ if A and B are the same process, $n = 2$ otherwise

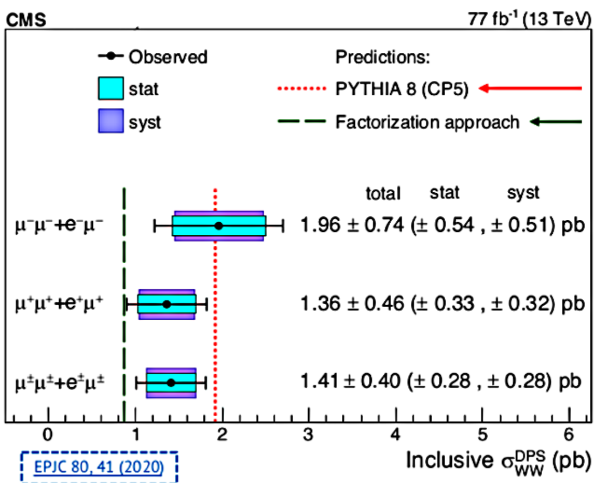
Assuming no parton correlations:
σ_{eff} directly measures proton transverse parton profile:

$$\sigma_{\rm eff,DPS} = \left[\int d^2b\, T^2(\mathbf{b})\right]^{-1}$$

- 3.9σ evidence of DPS ssWW. Effective x-section: $\sigma_{eff} = 12.7^{+5.0}_{-2.9}$ mb



EPJC 80, 41 (2020)



EPJC 80, 41 (2020)

	Value	Significance (standard deviations)
$\sigma^{\rm PYTHIA}_{\rm DPS\,WW,exp}$	1.92 pb	5.4
$\sigma^{\rm factorized}_{\rm DPS\,WW,exp}$	0.87 pb	2.5
$\sigma_{\rm DPS\,WW,obs}$	1.41 ± 0.28 (stat) ± 0.28 (syst) pb	3.9
$\sigma_{\rm eff}$	$12.7^{+5.0}_{-2.9}$ mb	—

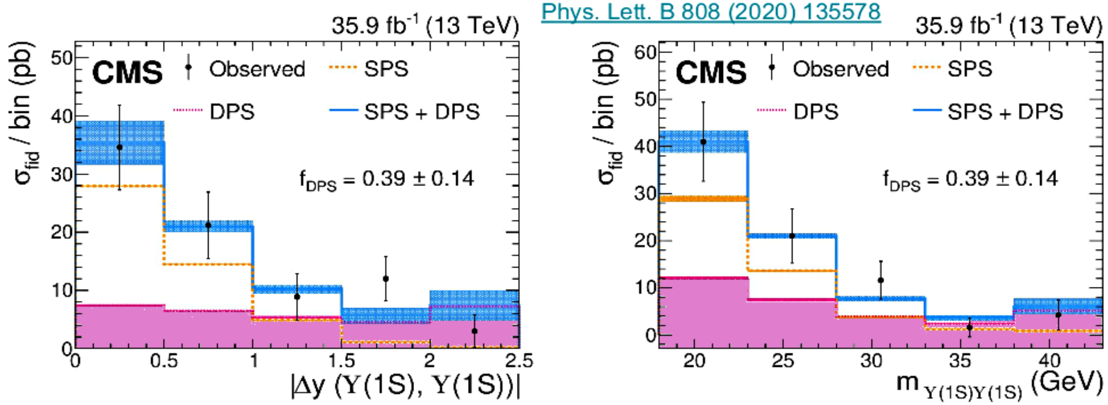
Step towards ultimate accurate determination of proton parton transv. profile & parton correlations at LHC energies.

[R.Salvatico/CMS]

Double Parton Scattering: Double Υ, J/φ+W

- DPS production amounts to ~35% of double-Υ cross section:

CMS-BPH-18-002
Phys. Lett. B 808 (2020) 135578

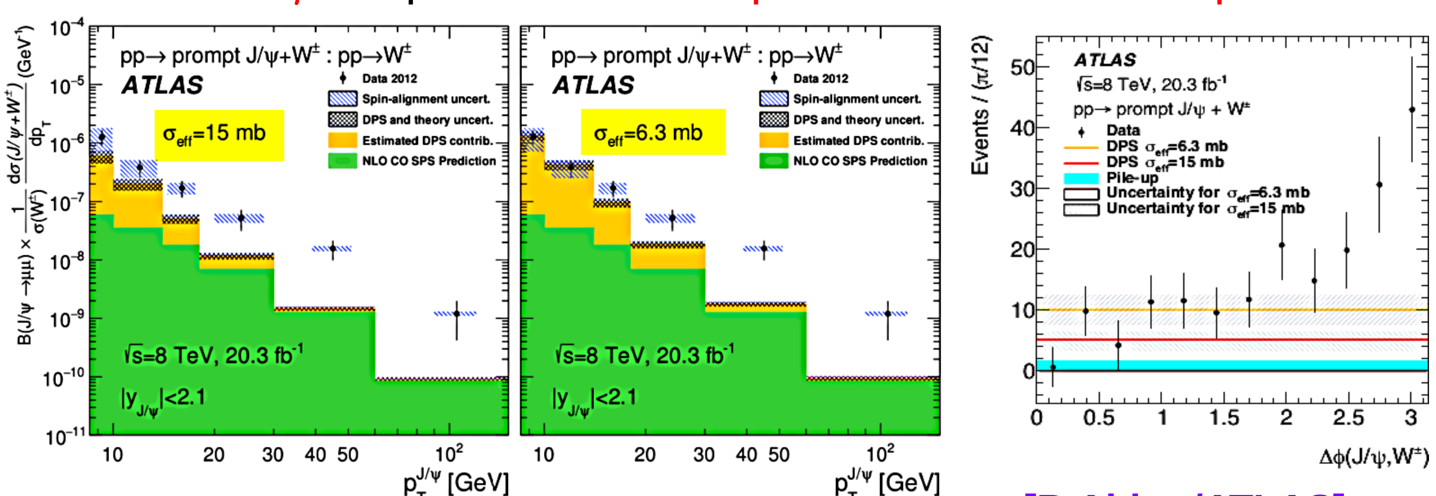


[S.Amaral/CMS]

Extra input to world σ_{eff} systematics

$$f_{DPS} = \frac{\sigma^{DPS}_{fid}}{\sigma^{SPS}_{fid} + \sigma^{DPS}_{fid}} = \begin{cases} (39 \pm 14)\% & using\ |\Delta y(\Upsilon(1S), \Upsilon(1S))| \\ (27 \pm 22)\% & using\ m_{\Upsilon(1S),\Upsilon(1S)} \end{cases}$$

- DPS with J/φ+W probes different parton flavour tranvs. profile than double-Q$\bar{\mathrm{Q}}$:

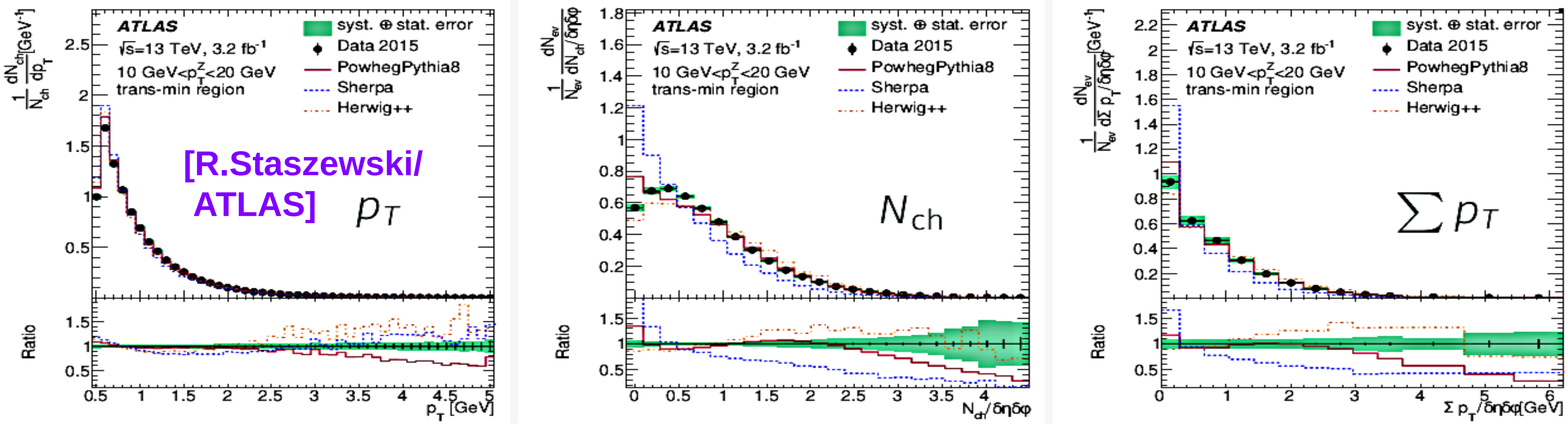


Effective pp x-section tested: σ_{eff} = 6–12 mb (lower value preferred)

[B.Abbot/ATLAS]

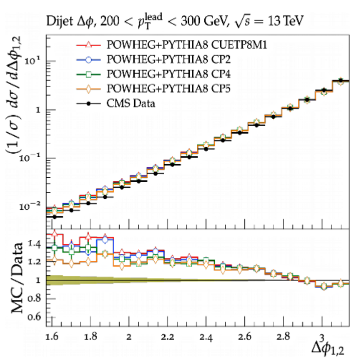
Updated MPI settings for NLO+PS. Universal UE.

- ATLAS Z-jet UE data confirm need of NLO+PY8, SHERPA, HERWIG retuning:



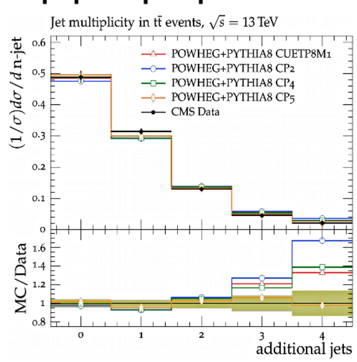
- Updated CMS NLO+PY8/HWG MB tunes reproduce many hard-scatt. UE data:

Multijet final states



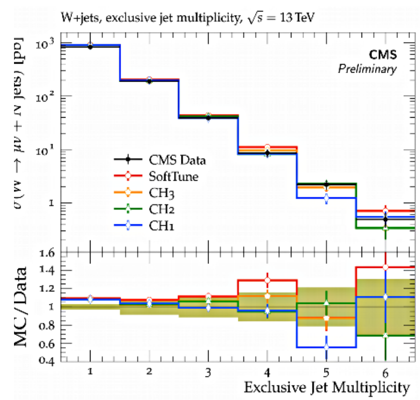
- **NLO dijet ME** in `Powheg` merged with `Pythia 8`
- **Tunes based on NLO α_s running better** than tunes with LO running (lower α_s^{FSR} → less jet decorrelation)

Top quark pair production



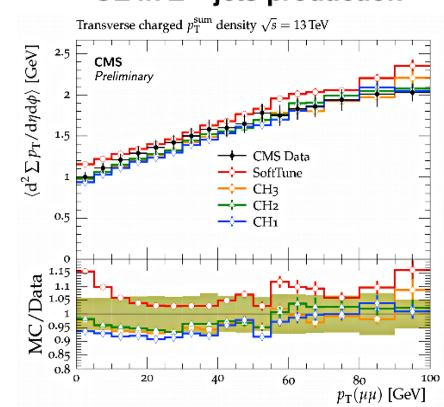
- Interfacing **NLO** `Powheg` or `MG5_aMC@NLO` ME with `Pythia 8`
- **α_s = 0.118 + rapidity ordering** of ISR (= CP5 tune) **favored** for `Powheg + Pythia 8`

W/Z + jets production



- **NLO ME** calculations up to 2 additional partons `MG5_aMC@NLO + Herwig 7[FxFx]`
- ME (PS) dominates at low (high) jet mult.

UE in Z + jets production

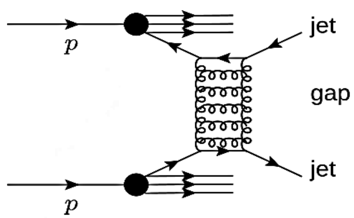


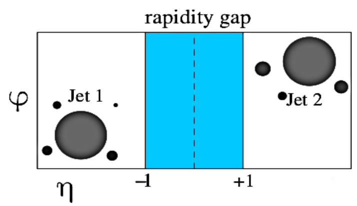
- Checks UE description at higher scales than MB data
- **CH3 tune describes data well**

[G.VanOnsem/CMS]

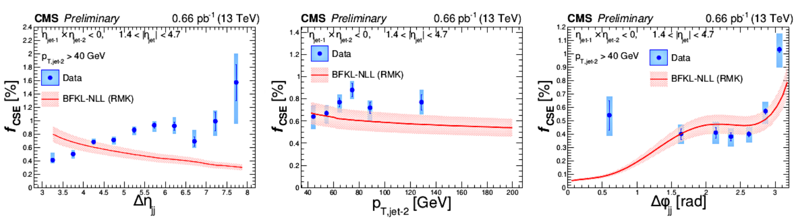
Hard diffractive scatterings

- 1st measurement of jet-gap-jet (Mueller-Tang dijets)





Key process to test BFKL dynamics.



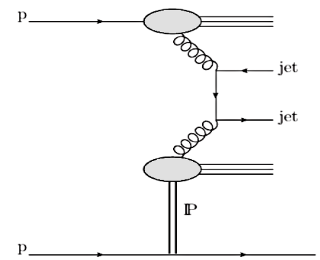
CMS-PAS-SMP-19-006

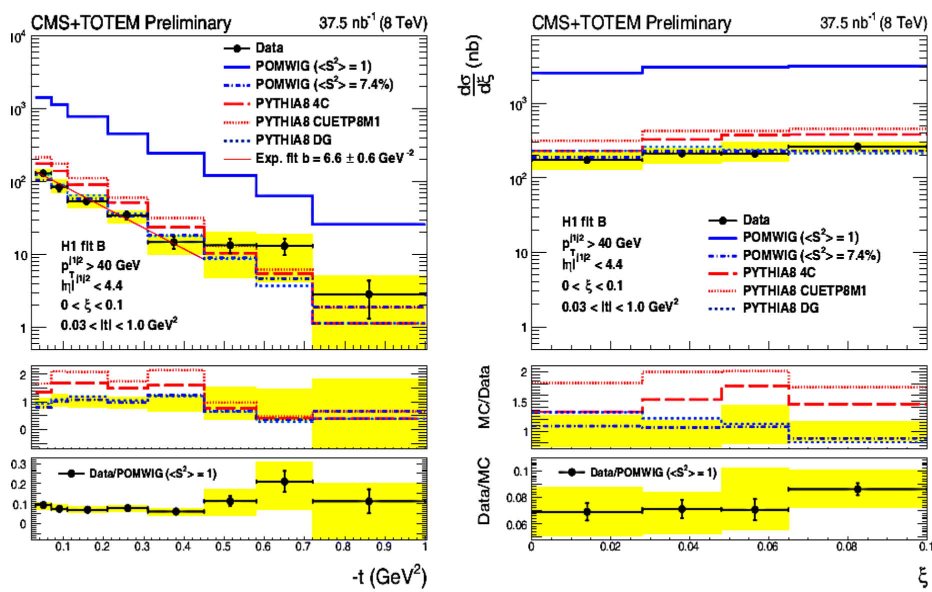
- $f_{\rm CSE}$ generally increases with increasing $\Delta\eta_{jj} \equiv |\eta_{j1} - \eta_{j2}|$. Weak dependence of $f_{\rm CSE}$ on $p_{T,j2}$ within uncertainties. $f_{\rm CSE}$ increases at $\Delta\phi_{jj} \equiv |\phi_{j1} - \phi_{j2}| \approx \pi$, uniform at $\Delta\phi_{jj} < 2.7$. Typical values of $f_{\rm CSE} = 0.6$–1.0%.
- Comparison to Royon, Marquet, Kepka (RMK) model based on BFKL NLL calculations + LO impact factors (Phys. Rev. D 83.034036), and survival probability $|S|^2 = 0.1$.
- Challenging to describe all features of the measurement simultaneously → Guidance for further theory development.

Rap-gap survival probab.: 0.6–1.0%
Differential distributions not well reproduced by models.

[C.Baldenegro/CMS]

- Single-diffraction dijets with fwd. proton tag:





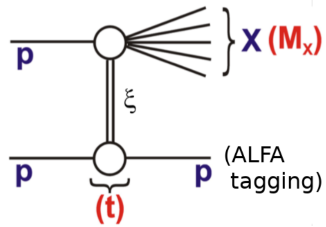
$$\sigma_{jj}^{pX} = 21.7 \pm 0.9 \text{ (stat)} {}^{+3.0}_{-3.3} \text{ (syst)} \pm 0.9 \text{ (lumi) nb}$$

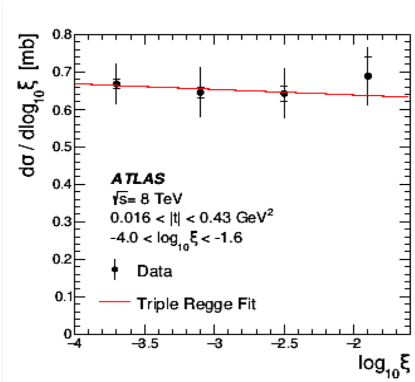
Test of rap-gap surv. probab. (~7%) in MCs:
PYTHIA 8 DG & Pomwig models: OK
PYTHIA 8 4C & CUETP8M1 too high

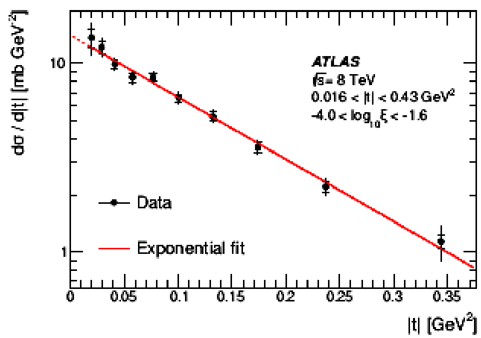
[O.Suranyi/CMS-TOTEM]

Elastic & soft diffractive scatterings

- Precise single-diffractive data with forward proton tagging:







Pomeron intercept:

$$\alpha(0) = 1.07 \pm 0.02\,(stat.) \pm 0.06\,(syst.) \pm 0.06\,(\alpha')$$

PYTHIA 8 A3 (Donnachie-Landshoff): α(0) = 1.14

PYTHIA 8 A2 (Schuler-Sjostrand): α(0) = 1.00

Elastic slope:

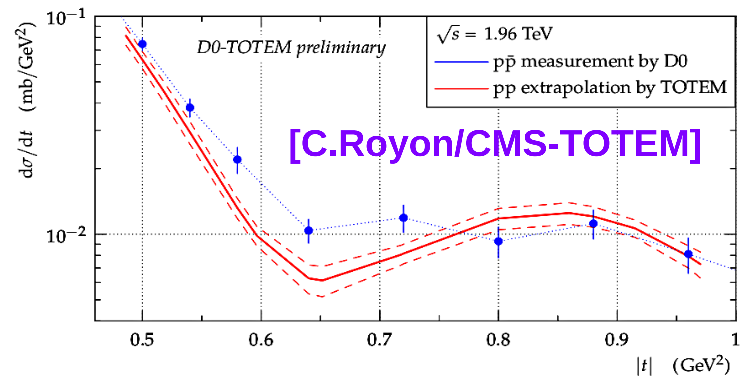
$$B = 7.60 \pm 0.23\,(stat.) \pm 0.22\,(syst.)\ \mathrm{GeV}^{-2}$$

In agreement with Pythia 8 prediction:

PYTHIA8 A2: 7.82 GeV^{-2}, PYTHIA8 A3: 7.10 GeV^{-2}

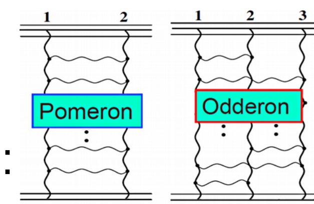
[R.Staszewski/ATLAS]

- D0+TOTEM analysis of elastic p-p:

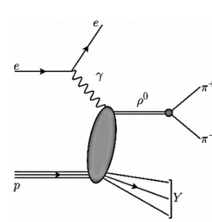


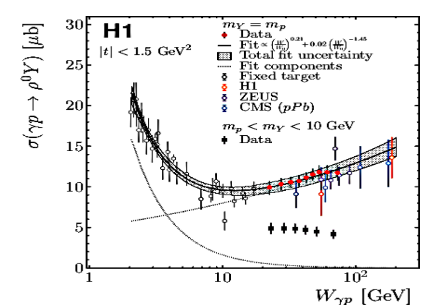
[C.Royon/CMS-TOTEM]

Differences suggestive of Odderon (3-gluon) exchange in p-p at LHC:



- Other soft diffraction results (ϱ photoproduction, CEP $\pi\pi$,...)

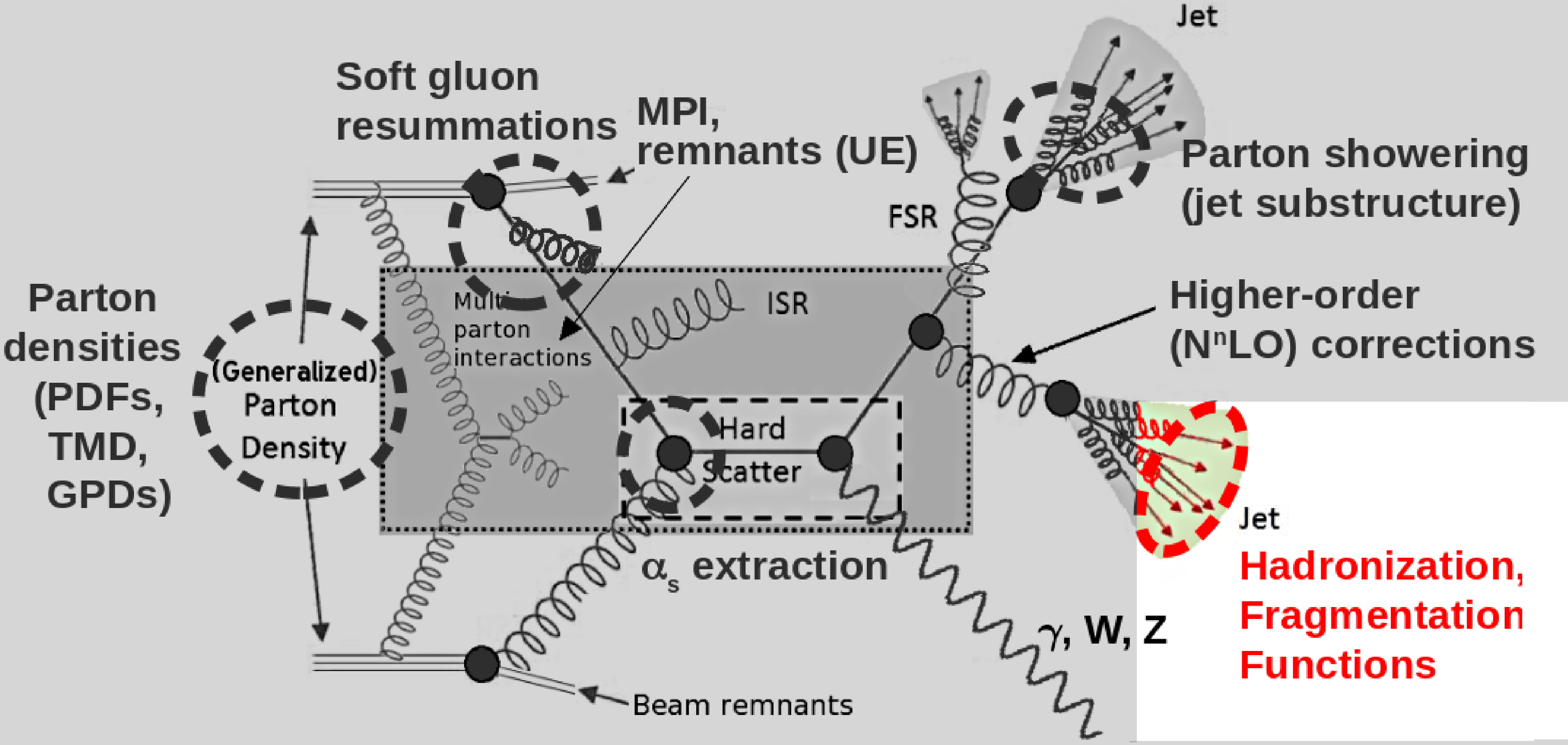




[A.Boltz/H1] [R.Sikora,T.Truhlar/STAR]

(7) Parton hadronization

- Typical proton-proton collision at the LHC:

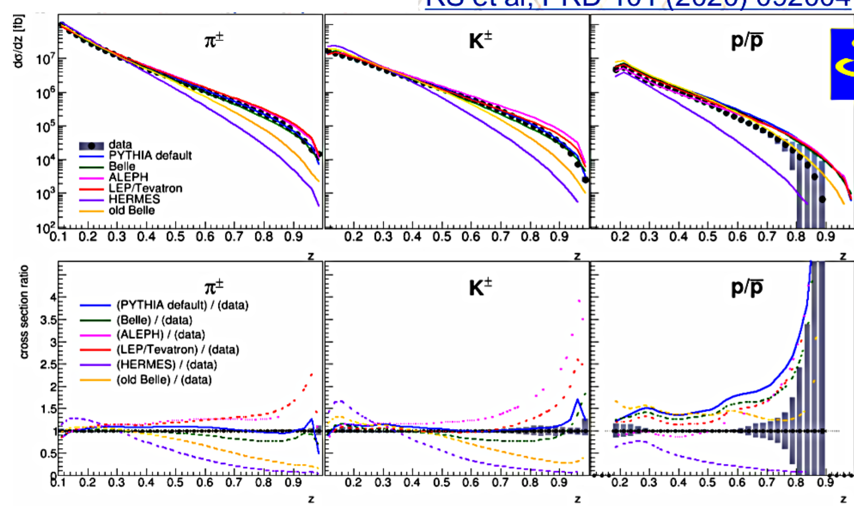


Light-quark & gluon fragmentation functions

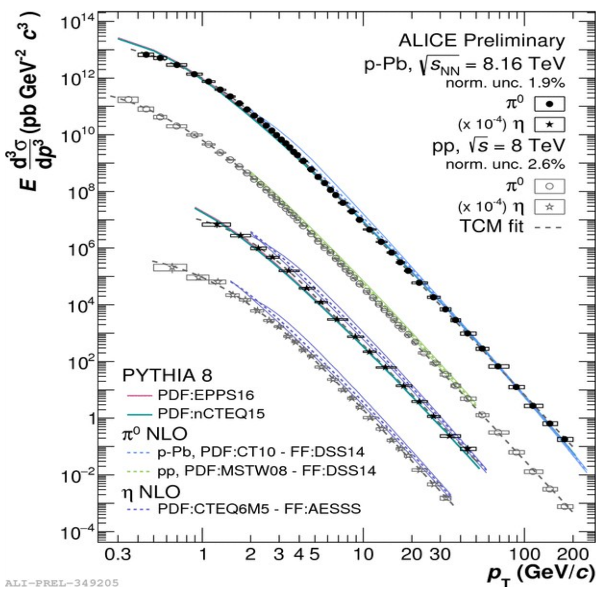
- High-precision BELLE π,K,p FFs: Default PY8 can reproduce π,k, but proton production remains challenging for MCs even in e^+e^-.

[R.Seidl/BELLE]

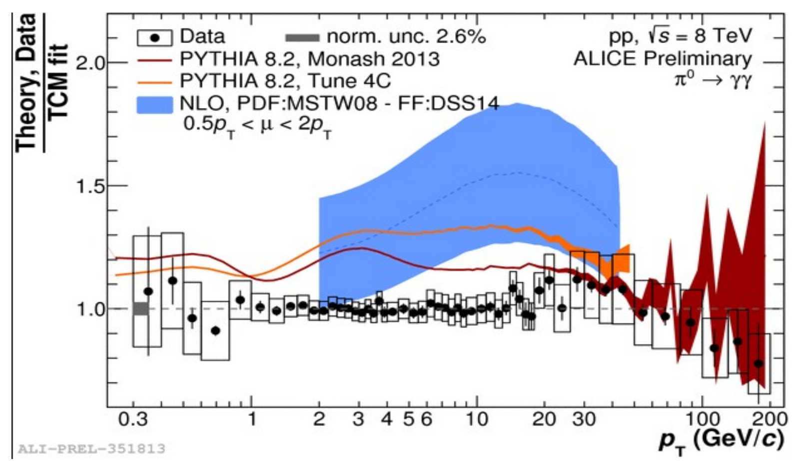
RS et al, PRD 101 (2020) 092004



- π^0, η production at the LHC over p_T=0.3–200 GeV



[F.Jonas/ALICE]



Difficulties to reproduce meson production with e^+e^- NLO FFs (or with PY8) over p_T=2–20 GeV:

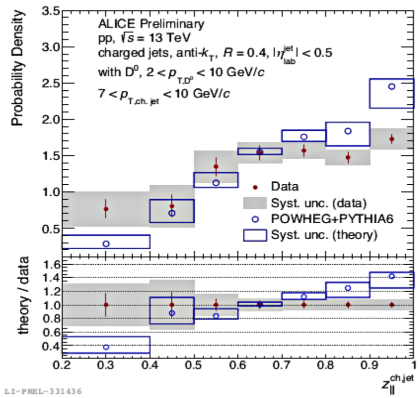
Gluon→π FFs well constrained in e^+e^-? Universal FF?

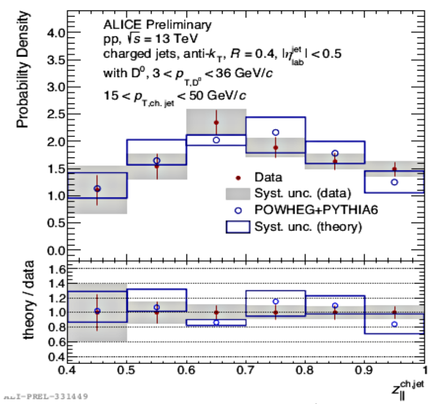
Heavy-Q fragmentation functions

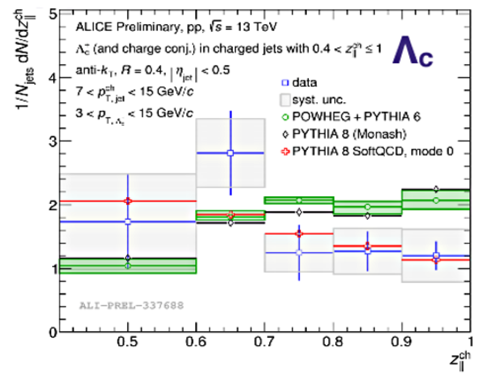
- Charm jet FFs with leading D^0 mesons & Λ_c baryons:

[M.Mazzilli/ALICE]

pp @ $\sqrt{s}$ = 13 TeV







Momentum fraction carried by the D^0 meson in the direction of the jet axis: $z^{ch}_{||} = \frac{\vec{p}^{\,ch}_{jet} \cdot \vec{p}_{HF}}{\vec{p}^{\,ch}_{jet} \cdot \vec{p}^{\,ch}_{jet}}$

Good agreement with NLO (POWHEG+PYTHIA6) pQCD predictions for higher $p_{T,jet}$

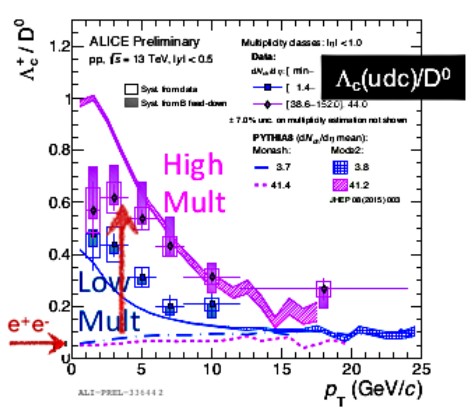
PYTHIA6: JHEP 05, 026 (2006)
PYTHIA8: Comput. Phys. Commun. 178, 852–867 (2008)
POWHEG: JHEP 11, 040 (2004), JHEP 1200 11, 070 (2007)

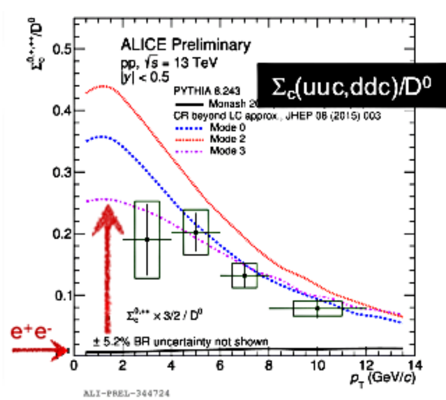
Measurements point towards a softer fragmentation at lower $p_{T,jet}$

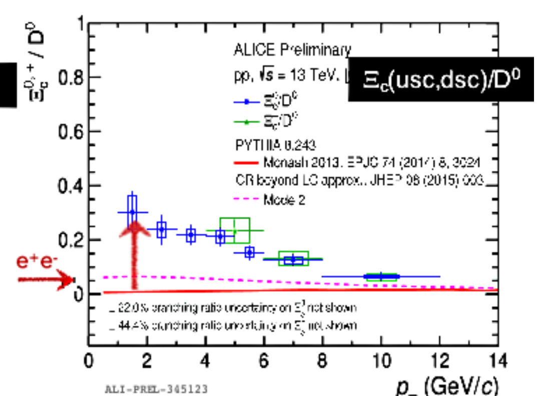
Decent agreement with NLO POWHEG+PYTHIA, except for low-p_T charm jet (softer FF in data).

- Ratio of Λ_c, Σ_c, Ξ_c baryons over D^0 meson production:

[J.Zhu/ALICE]







Λ_c/D^0 ~ x10 larger than in e+e-, PYTHIA color reconnection tune Mode 2 ✔

Σ_c/D^0 x20-30 larger than in e+e-, PYTHIA color reconnection tune Mode 0,2 ✔

Ξ_c/D^0 x20-30 larger than in e+e-, PYTHIA color reconnection tune Mode 2 ✗

Heavy-charm baryon production very enhanced in pp w.r.t. e^+e^- collisions.

~33% (6%) of charm baryonize in pp (ee).

Significant FS color reconnection needed.

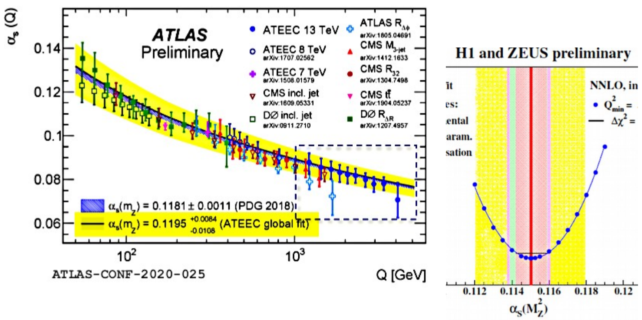
Summary: Experimental QCD at ICHEP'20

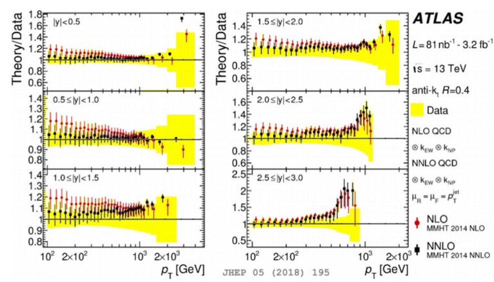
- ☛ The precision needed to fully exploit the SM & BSM programs at the LHC requires exquisite control of pQCD & non-pQCD physics.
- ☛ Vast number of increasingly precise QCD observables experimentally studied. Lead to improved analytic & MC models:

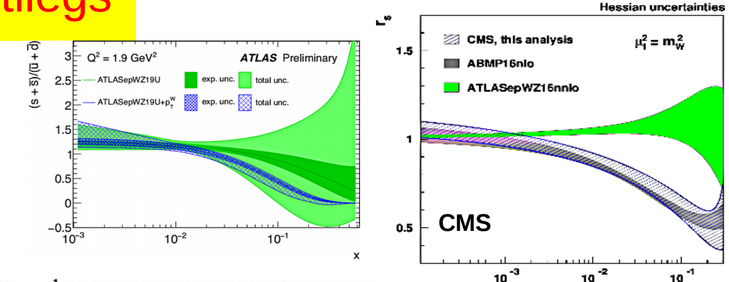
(1) New α_s extractions

(2) Data vs. N^nLO & multilegs

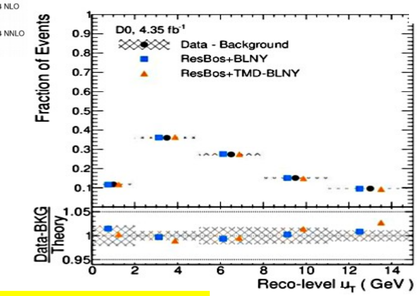
(3) Improved PDFs

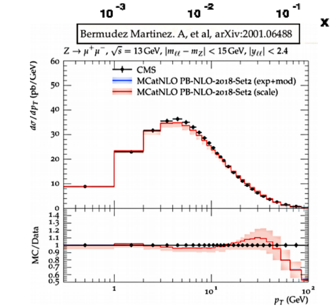




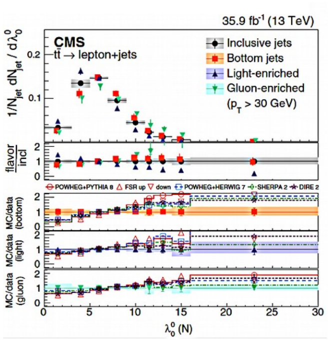


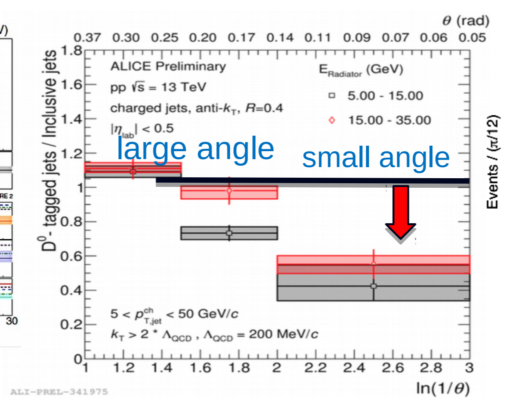
(4) Data vs. N^nLL resummations:



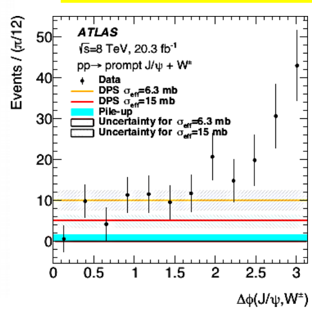


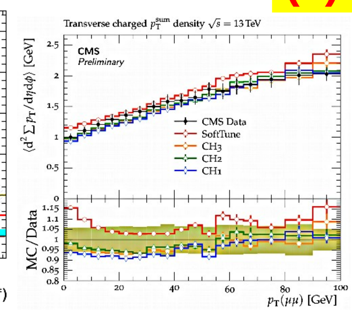
(5) Advanced jet substructure studies



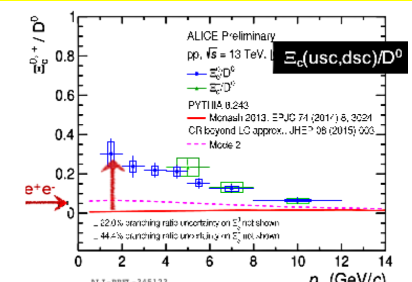


(6) DPS, MPI, UE,...





(7) Parton hadronization



Backup slides

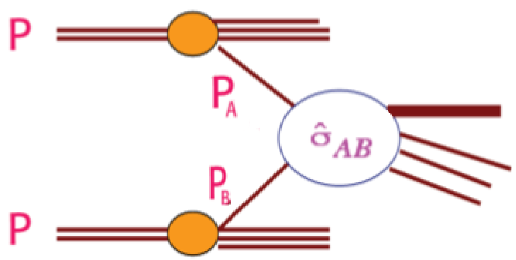
QCD = Fundamental ingredient at colliders

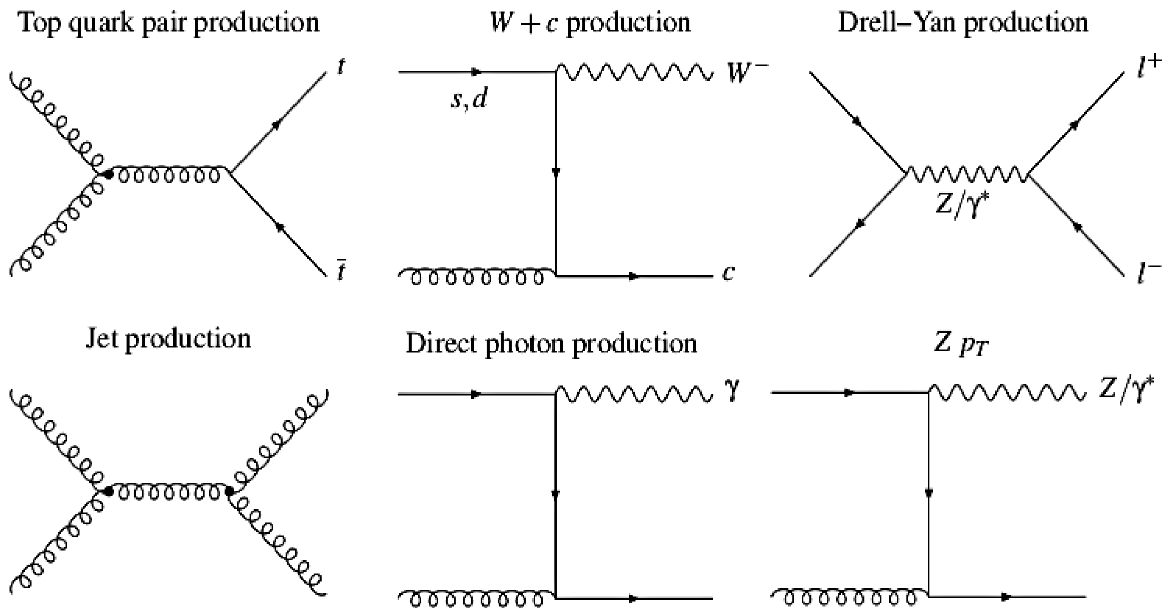
- Though *not being per se* main driving force behind current&future colliders, QCD is crucial for many pp,ee measurements (signals&backgds):
  - High-precision α_s: Affects all x-sections & decays (esp. Higgs, top, EWPOs).
  - N^nLO corrections, N^nLL resummations: Affect all pQCD x-sections & decays.
  - High-precision PDFs: Affect all precision W, Z, H (mid-x) measurements & all searches (high-x) in pp collisions.
  - Parton showering, Q/q/g separation (jet substructure, boosted topologies..): Needed for all precision SM measurements & BSM searches with final jets.
  - Semihard QCD (low-x gluon saturation, multiple hard parton interactions,…): Leading x-sections in pp collisions (Note: Q_0~4 GeV at 14 TeV).
  - Non-perturbative QCD: Affects final-states with jets: Colour reconnection, intrinsic k_T, parton hadronization,… Impacts m_W,m_{top},… extractions

Improving PDFs with proton-proton data

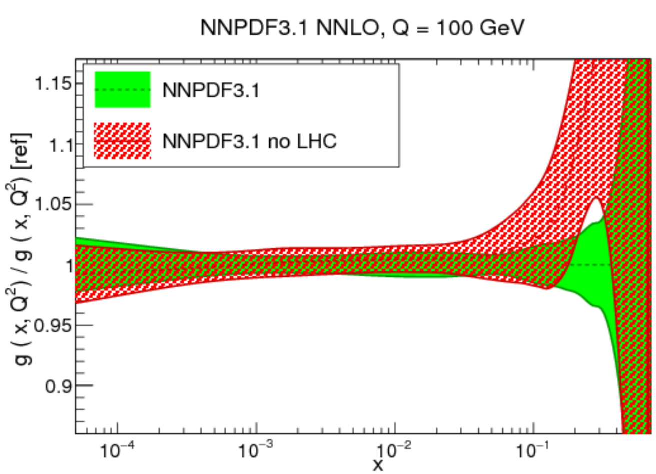
- 6 partonic processes in pp at the LHC have provided key PDF constraints:

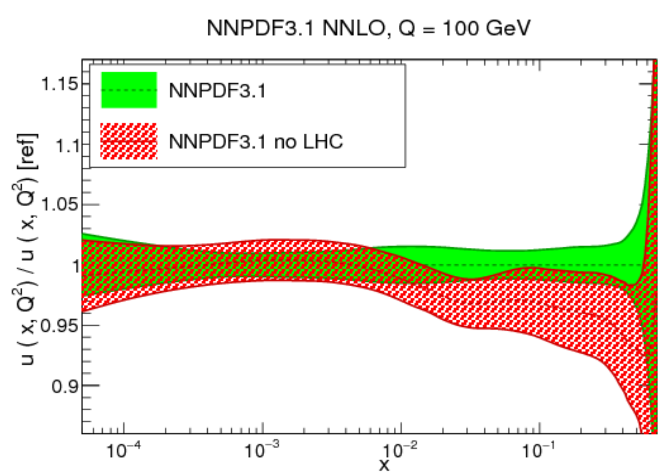
$$\sigma = \hat{\sigma} \otimes \mathrm{PDF}$$





- Improved NNLO g, u, ... PDFs already today using LHC data:



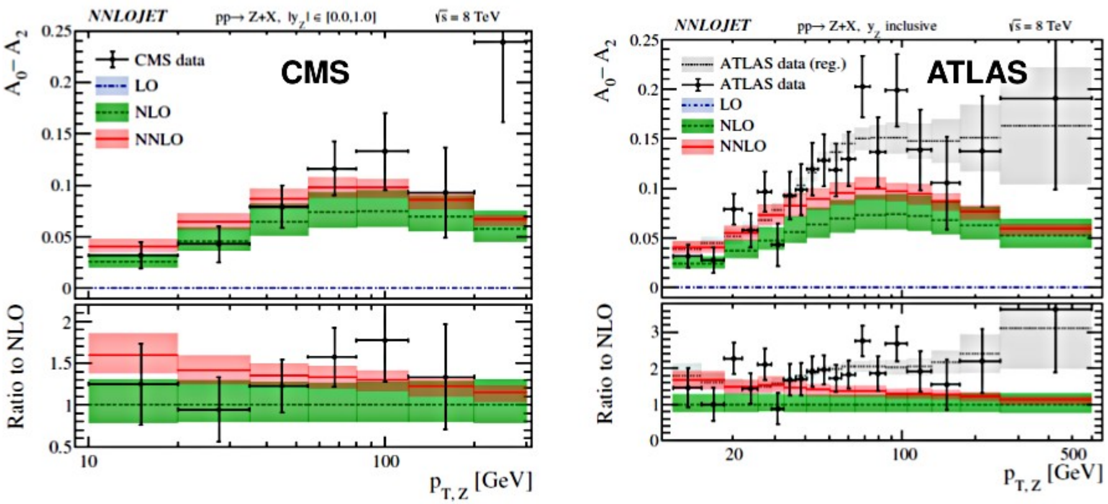


Data vs. pQCD at NNLO: Z angular distribs.

Lam-Tung Violation: $A_0 - A_2$

$LO : O(\alpha_s^1); NLO : O(\alpha_s^2); NNLO : O(\alpha_s^3)$

[./CMS]



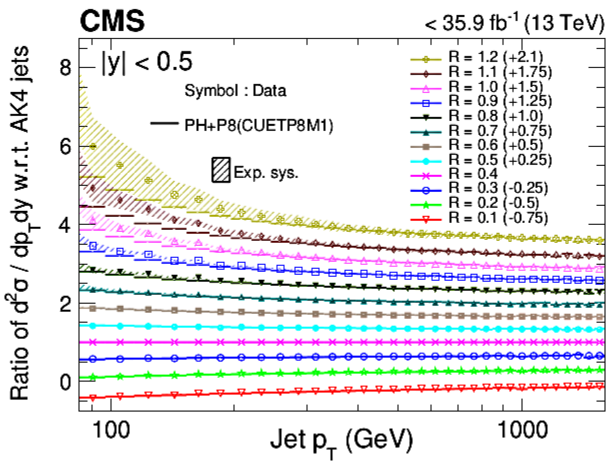
NLO (CMS):	$\chi^2/N_{data} = 24.5/14 = 1.75$	NLO (ATLAS):	$\chi^2/N_{data} = 185.8/38 = 4.89$
NNLO (CMS):	$\chi^2/N_{data} = 14.2/14 = 1.01$	NNLO (ATLAS):	$\chi^2/N_{data} = 68.3/38 = 1.80$.

[./ATLAS]

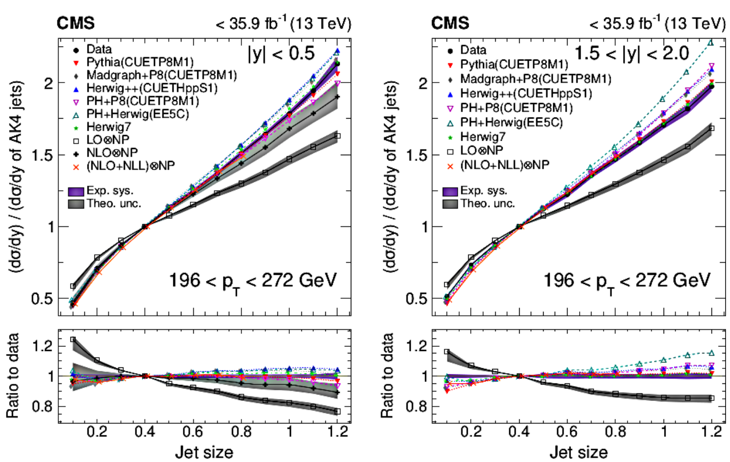
- Blabla

Parton shower: Radius scan, tri-jet events

- Jet x-section radius (ref. R=0.4) vs. p_T



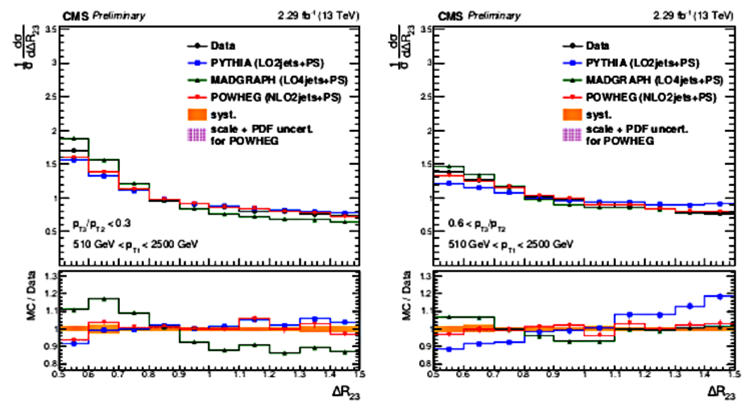
arXiv:2005.05159



arXiv:2005.05159

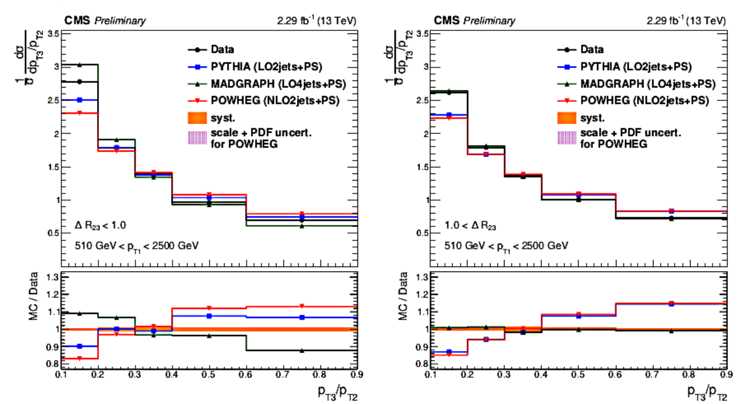
- Central region $|y| < 0.5$ (**Left**) and forward region $1.5 < |y| < 2.0$ (**Right**).
- Best agreement achieved by NLO predictions in general R parameter range.
- NLO predictions slightly overshoot data at larger R values in forward region.

- Tri-jet topologies: data vs. PS



CMS-PAS-SMP-17-008

- **Left**: small $p_{T3}/p_{T2} < 0.3$ (soft splitting) **Right**: large $p_{T3}/p_{T2} > 0.6$ (hard splitting)
- Powheg (NLO2jets+PS) gives best agreement in ΔR_{23} for soft p_T and hard p_T regimes.



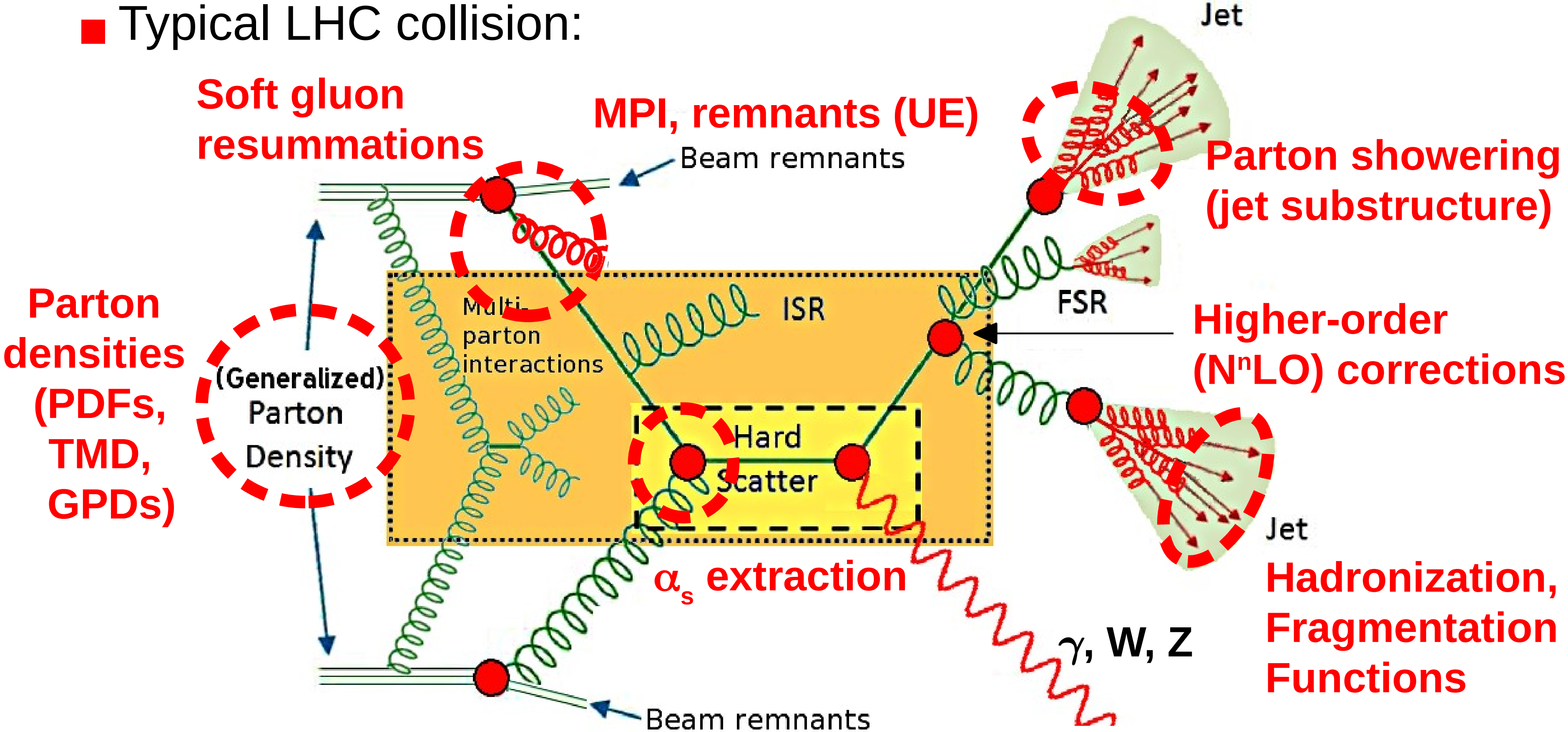
CMS-PAS-SMP-17-008

- **Left:** small-angle emissions $\Delta R_{23} < 1.0$ **Right:** wide-angle emissions $\Delta R_{23} > 1.0$.
- Powheg+Pythia8 (NLO2jets+PS) and Pythia8 (LO2jets+PS) are not able to describe data for small- and wide-angle emisisons in the soft- and hard-regimes in p_{T3}/p_{T2}.
- MadGraph (LO4jets + PS) is able to describe p_{T3}/p_{T2} spectra for wide-angle emissions $\Delta R_{23} > 1.0$. MadGraph does not describe well data for small-angle emissions $\Delta R_{23} < 1.0$.

[C.Baldenegro/CMS]

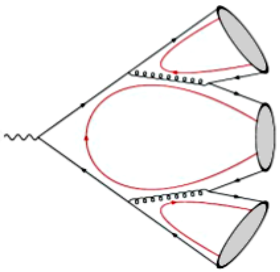
Organization of the talk

- Typical LHC collision:



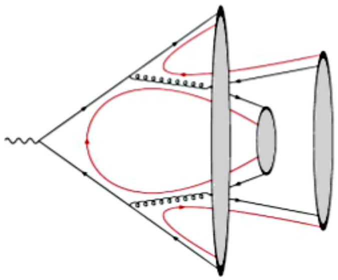
- All LHC observables depend chiefly on a precise control of all these, e.g.:
  i) BSM: heavy resonances (Z'): on precise high-x PDF, Instantons on UE,..
  ii) Higgs: b,c partial widths: on precise α_s coupling, …
  iii) W mass: on precise mid-x PDF, resummations, intrinsic k_T

Color reconnection



- **cluster hadronization**
  [Webber, Nucl. Phys. B238 (1984) 492]

- perturbative QCD provides *preconfinement*
  - colour-anticolour pairs form higly excited hadronic states = clusters
  [Amati, Veneziano, Phys.Lett. B83(1979)87]



- **Colour Reconnection**
  - partons before hadronizing may be modelled as they exchange gluons - an extra step to swap the colours

- improve description of soft MB events and UE

- effectively reduces cluster masses and thus the number of particles produced in the final state (with higher momentum)

  [S. Gieseke, C. Rohr, A. Siodmok, Eur. Phys. J C72 (2012) 2225]
  [S. Gieseke, P. Kirchgasser, S. Platzer, A. Siodmok, JHEP 1811 (2018) 149]
  [S. Gieseke, P. Kirchgasser, S. Platzer, Eur. Phys. J C78 (2018) no.2, 99]
  [S. Gieseke, P. Kirchgasser, S. Platzer, A. Siodmok, Acta Phys. Polon. B50 (2019) 1871]

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