# QCD and Hadronic Final States
# Working Group Summary

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with Shima Shimizu & Frank Tackmann

at
DIS 2016, Hamburg


# QCD and Hadronic Final States

Ten sessions, two of them joint – comprehensive coverage of the field

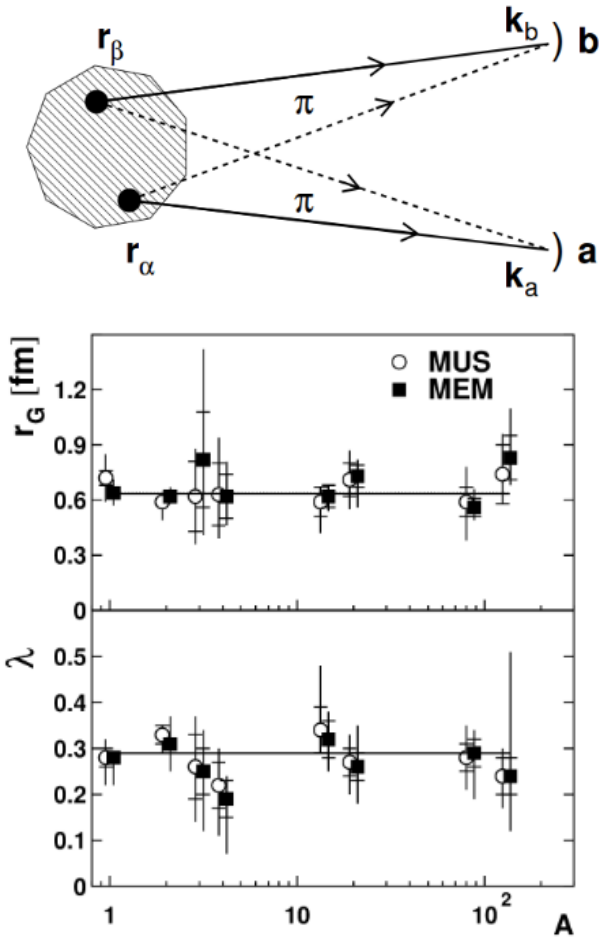
- → Hadronisation & Multiparticle correlations
- → Heavy Ions & Photons
- → Spectroscopy & Exotics
- → Jets & PDFs (with WG1 – see next talk)
- → V's & Jets (with WG3)
- → Precision Predictions
- → Monte Carlos & Multijet Production (two sessions)
- → Underlying Event
- → Double Parton Scattering

# Hadrons

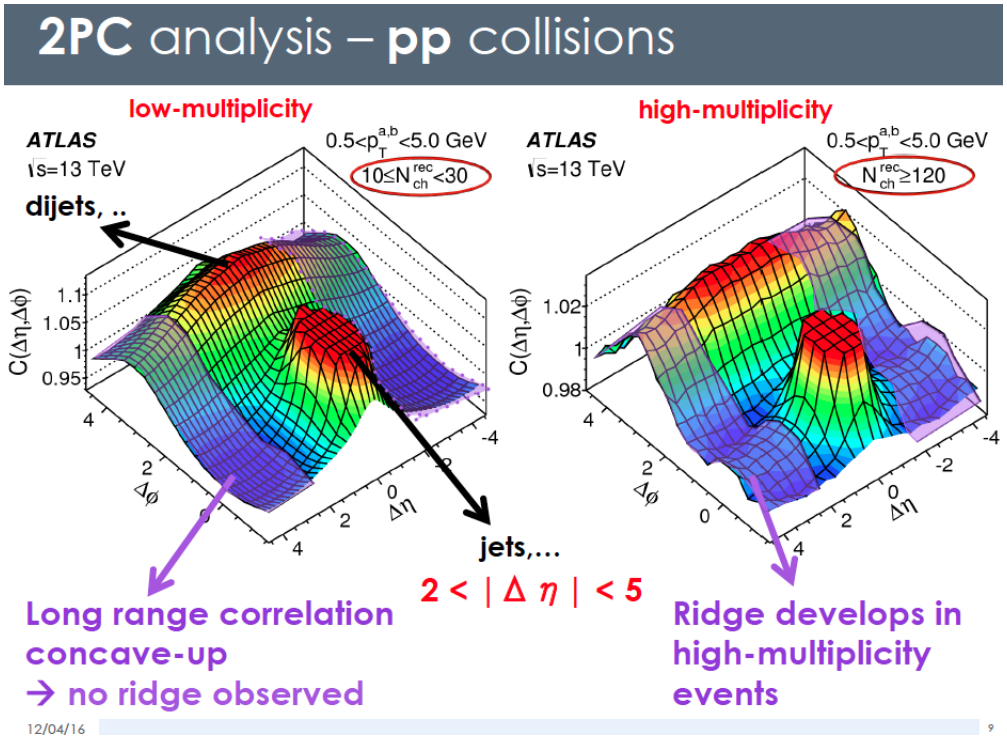
# Bose-Einstein and Ridge Correlations

**Measure correlation function:**
**Independent of A.**

[Burka – ATLAS]




[Karyan – HERMES]

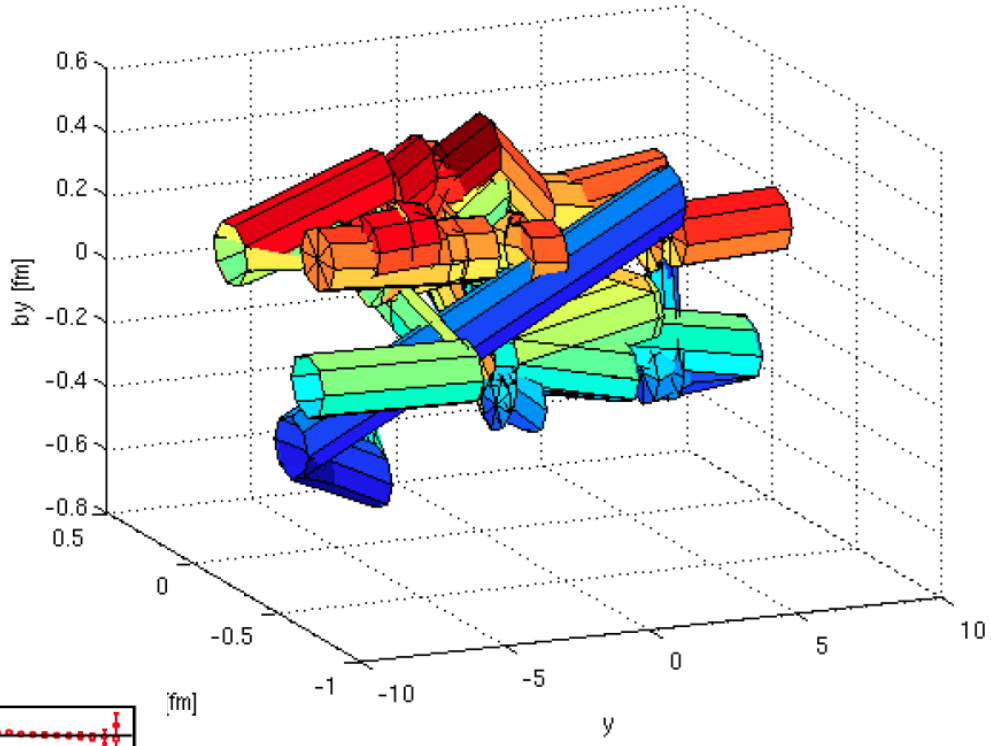


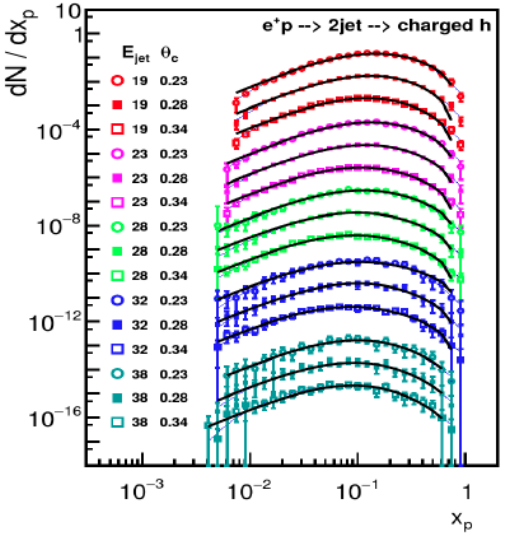

**Ridge appearing in pp/pA/AA high multiplicity events.**
**Allows to extract v2.**

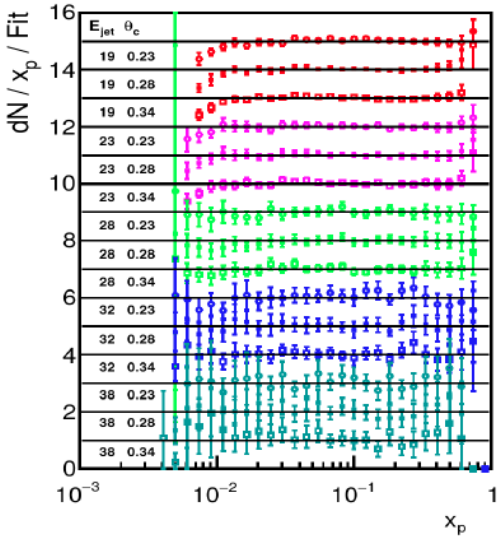
# Hadronisation and Colour Reconnection

[Bierlich]

MPI challenge hadronisation models.
Improving string hadronization.
Space-time picture seems necessary.
Better description of flavour data.



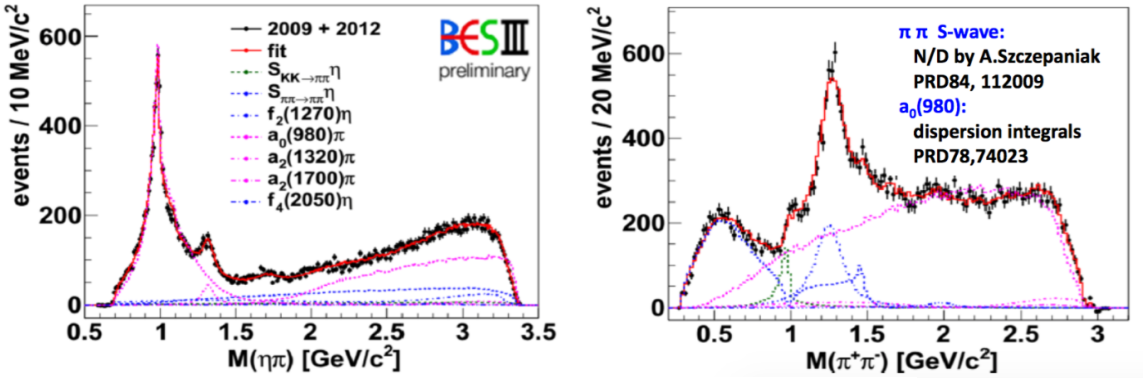




[Urmossy]

Statistical hadronisation model:
Ansatz for fragmentation functions.

# Spectroscopy

## [Pelizaeus – BESIII]



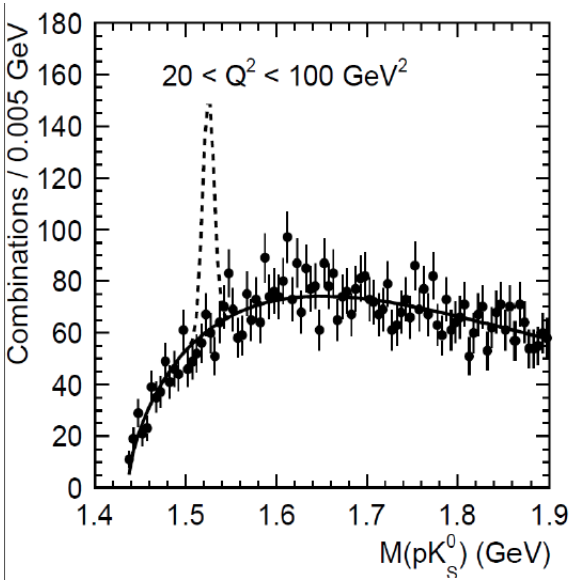

Measurement of $a_0(980)$ couplings

| Experiment | BESIII | CLEO-c[1] |
|---|---|---|
| $m_0$ [GeV/$c^2$] | 995.5±2.4±6.5 | 998±16 |
| $g^2_{\eta\pi}$ [GeV/$c^2$] | 0.368±0.003±0.013 | 0.36±0.04 |
| $g^2_{KK}/g^2_{\eta\pi}$ | 0.93±0.03±0.09 | 0.87±0.15 |
| $g^2_{\eta'\pi}/g^2_{\eta\pi}$ | 0.49±0.05±0.10 | 0.00±0.17 |

Deviation from 0

**Detailed Spectroscopy of objects such as X(1835) and a(980): Measuring couplings.**

## [Hori – ZEUS]



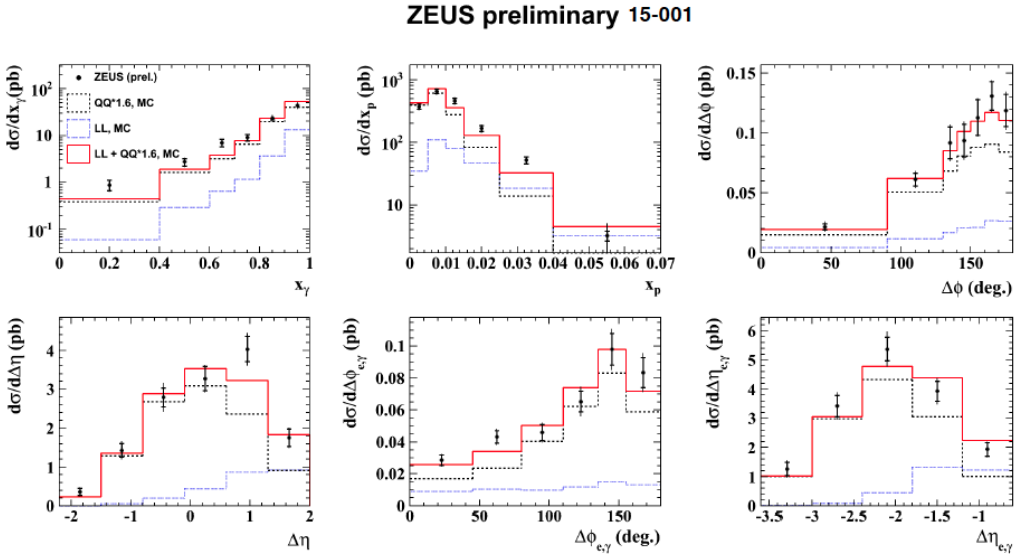

**No pentaquarks in HERA II data. Dashed line shows HERA I expectation.**

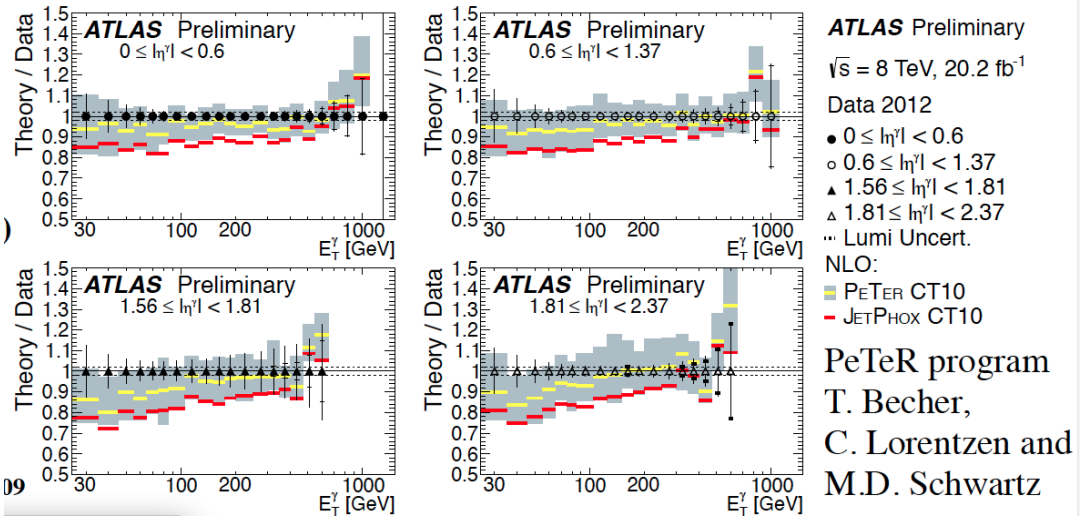
# DIS and more

# Photons: From HERA to the LHC

## [Hluschenko – ZEUS]

**Prompt photon production in DIS.**
**Reweighted LO MC describes data.**
**Kt factorization based models need more investigation.**




PeTeR program
T. Becher,
C. Lorentzen and
M.D. Schwartz

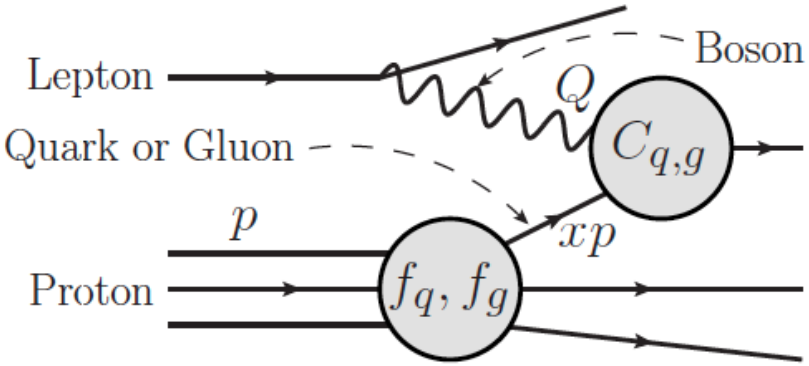
**ATLAS inclusive photons:**
**N3LL+NLO describes data well.**

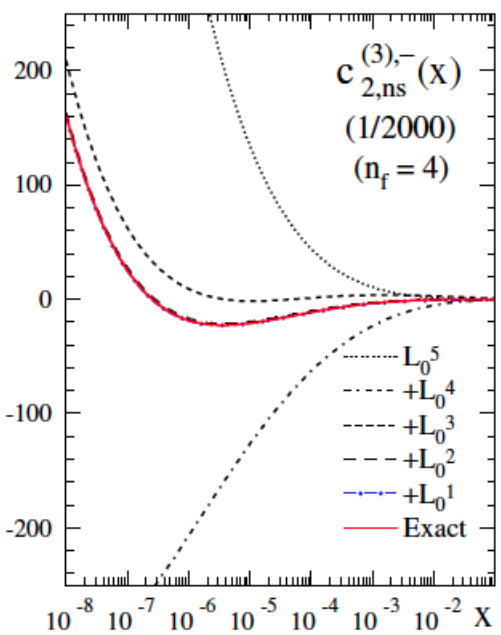
## [Terron – ATLAS]

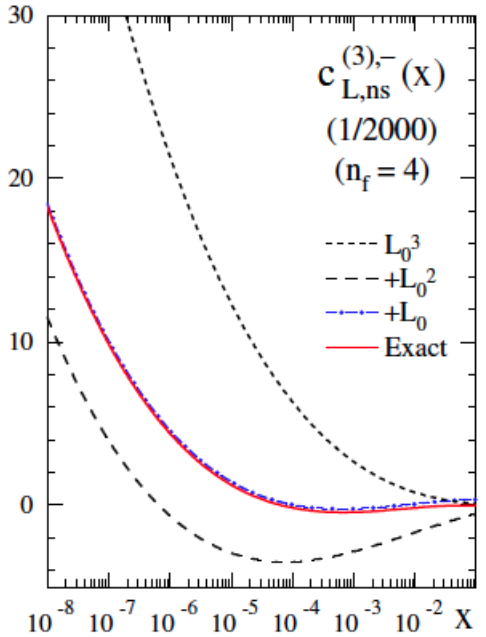
# Precision Charged Current DIS

[Davies]

**$W_+ - W_-$ probe in CC DIS:**
**Next step to completing 3rd order predictions.**
**Perturbative expansion seems to stabilize.**
**Poor convergence of small-x approximations.**



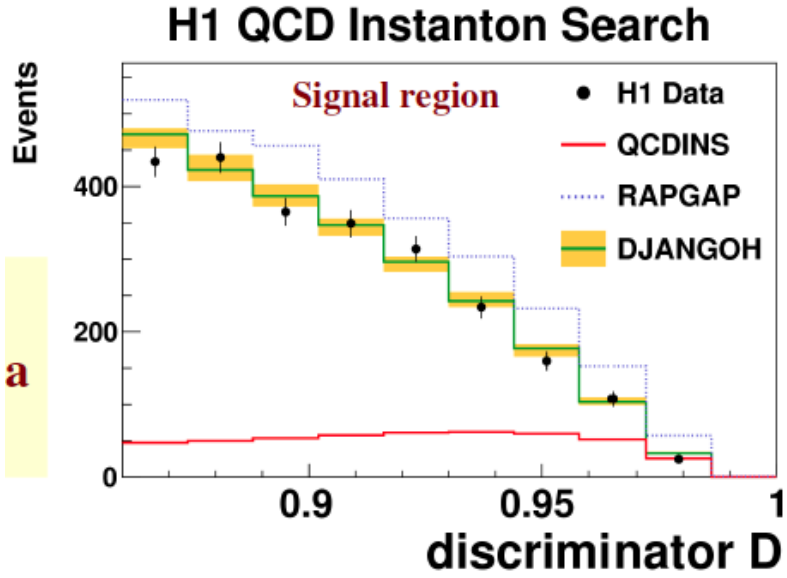



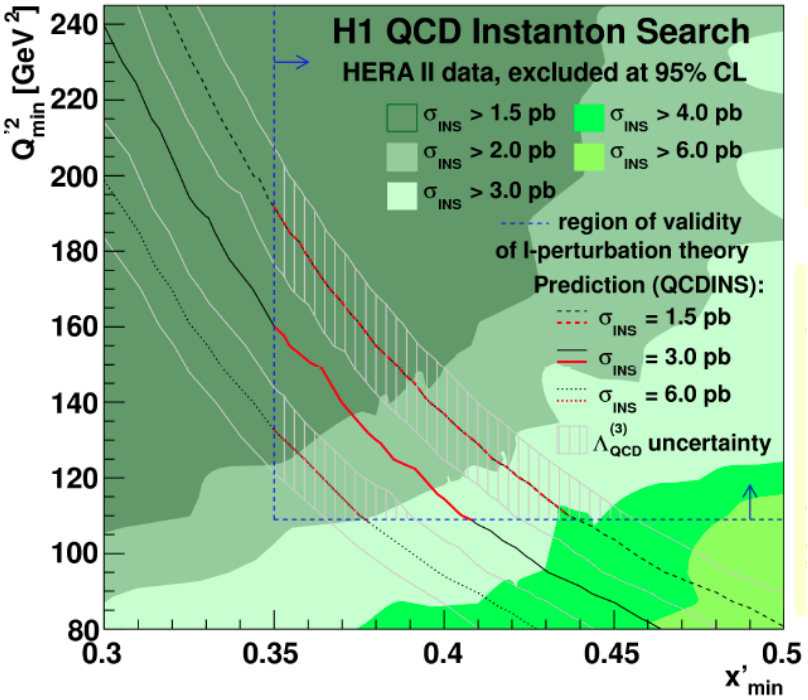

**No news for NuTeV anomaly.**

# QCD Instantons

[Mikocki – H1]

New limits on QCD instanton induced processes.
Spectacular signatures:
'Instanton bands'.




How reliable are background MCs?

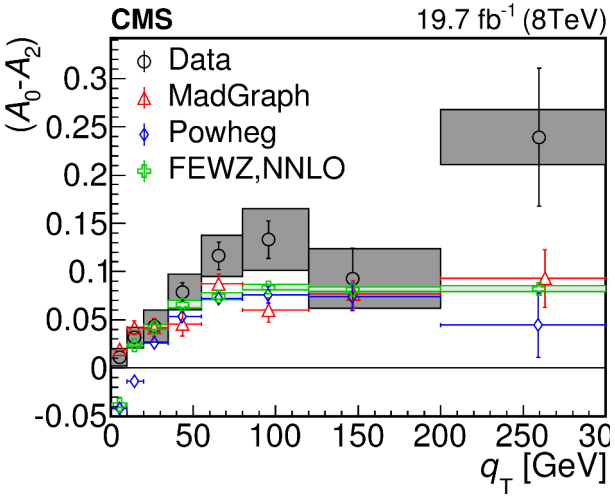
# Precision

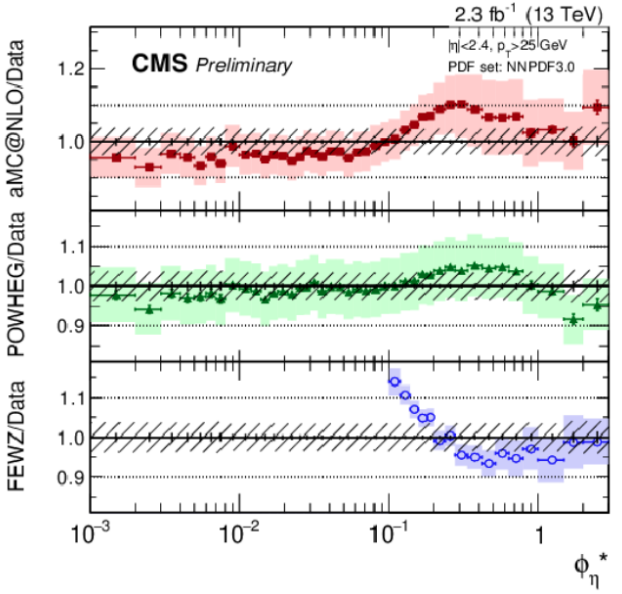
# Precision V's (and Jets)

Z/W pt related observables.
8 TeV and 13 TeV.

Loads of measurements:

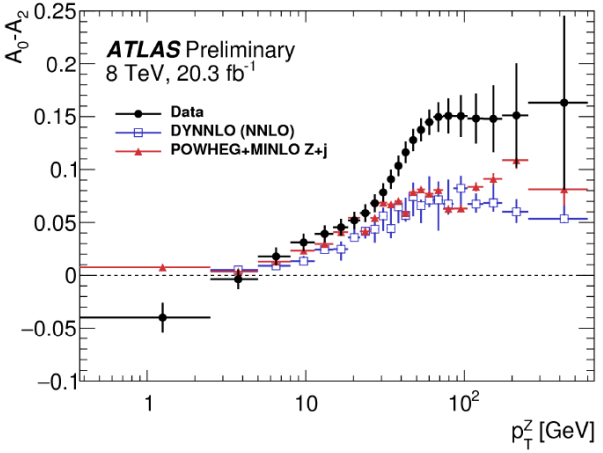
Z pt
Z phi*
Z angular coefficients
W charge asymmetry
Z forward/backward asym

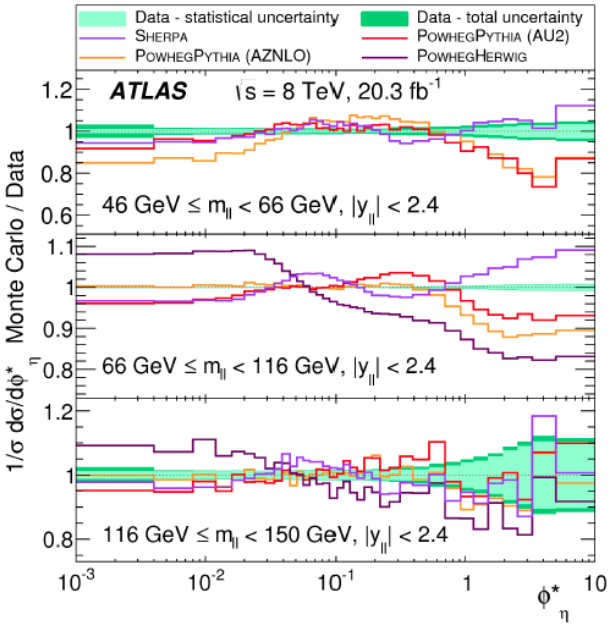



[Han – CMS]

[Ezhilov – ATLAS]



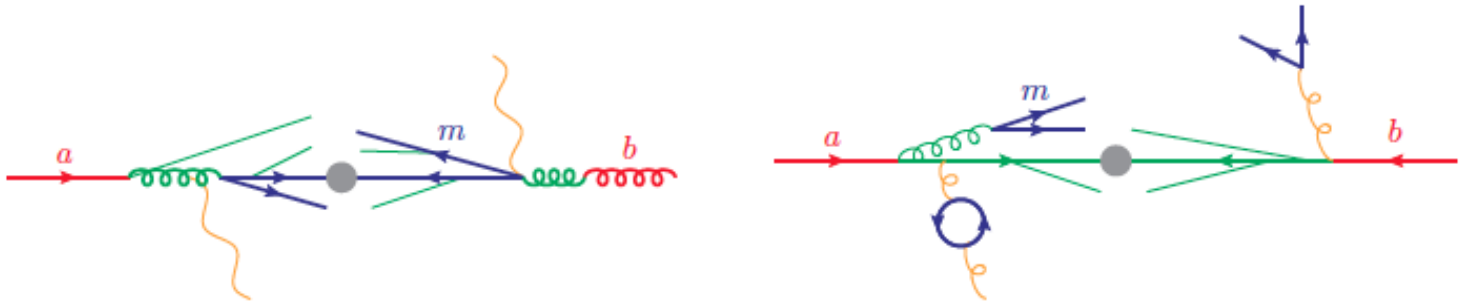



# Precision V's (and Jets)

[Pietrulewicz]

**Experimental precision needs to be backed up by accurate theory predictions.**

**Establish resummation with a systematic inclusion of quark mass effects.**

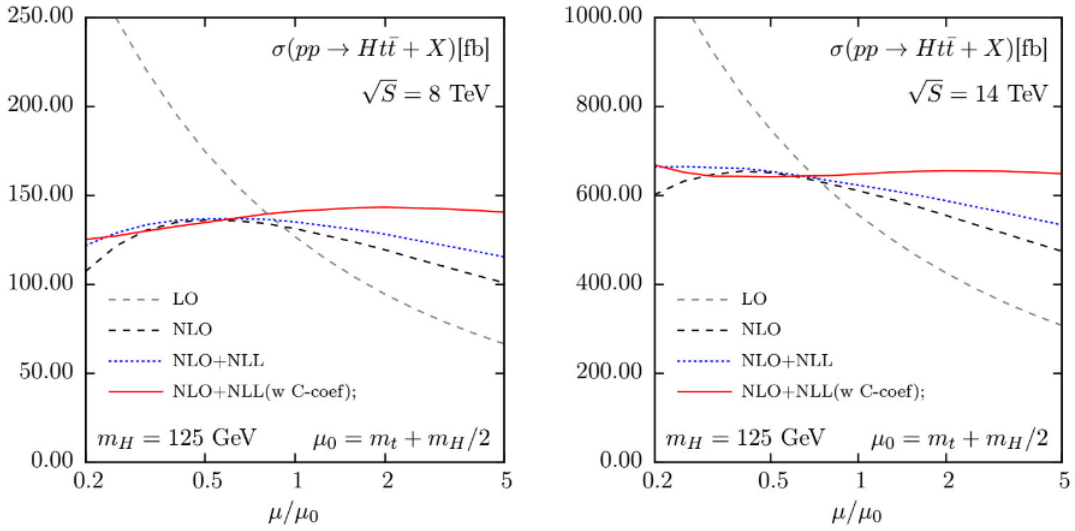



Factorization theorem: $(i,j \in \{q,\bar{q},Q,\bar{Q},g\}, k \in \{q,\bar{q},g\})$

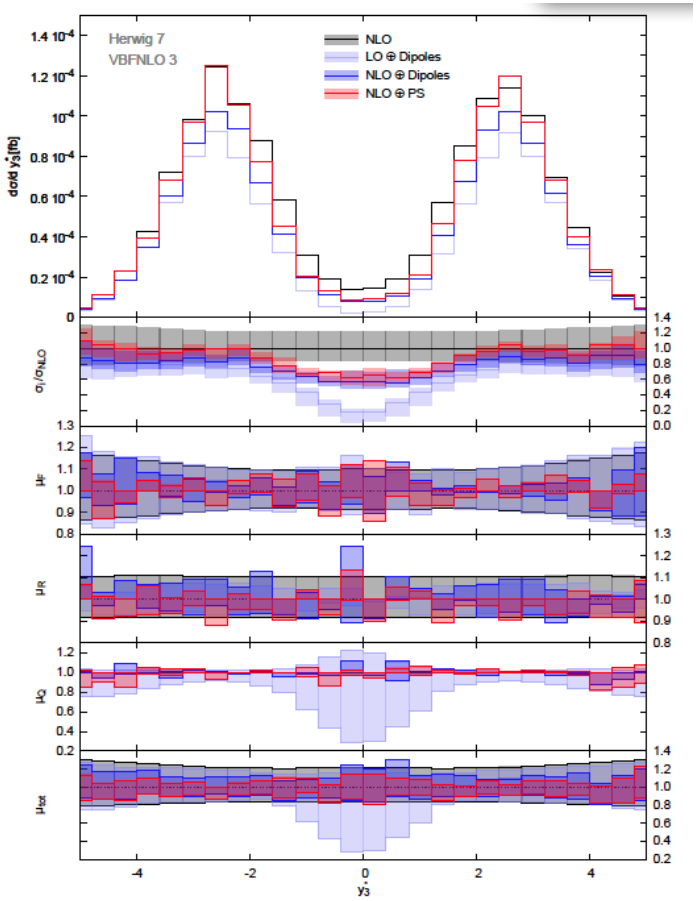
$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T^2} \sim \sum_{i,j} H_{ij}^{(n_l+1)} \times \left[\sum_k \mathcal{I}_{ik}(m) \otimes f_k^{(n_l)}\right]^2 \otimes S^{(n_l+1)}(m) + \mathcal{O}\left(\frac{m^2}{Q^2}, \frac{\Lambda_{\mathrm{QCD}}^2}{m^2}\right)$$

# QCD Effects in Higgs Production and VV scattering

[Stebel]




[Rauch]




**QCD precision for Higgs relevant processes:**

**Threshold resummation for ttH.**

**NLO+PS effects in VBF VV scattering with Herwig 7 + VBFNLO 3**

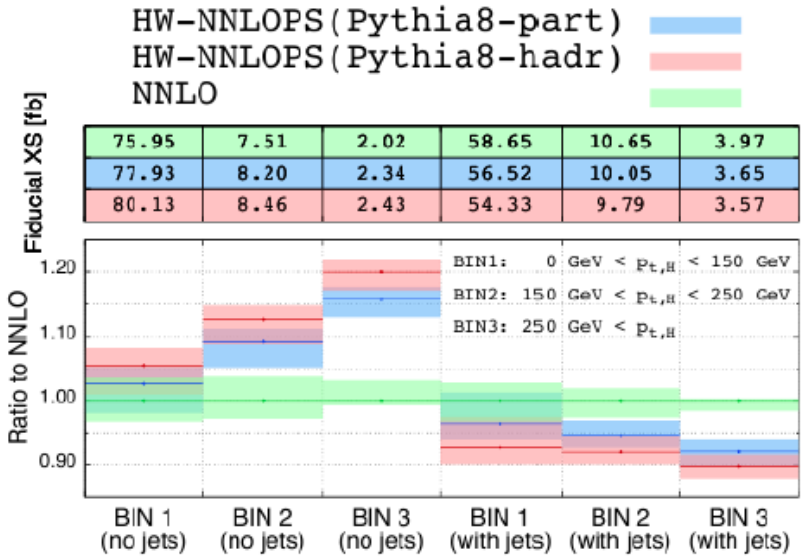
# NNLO + Parton Showers

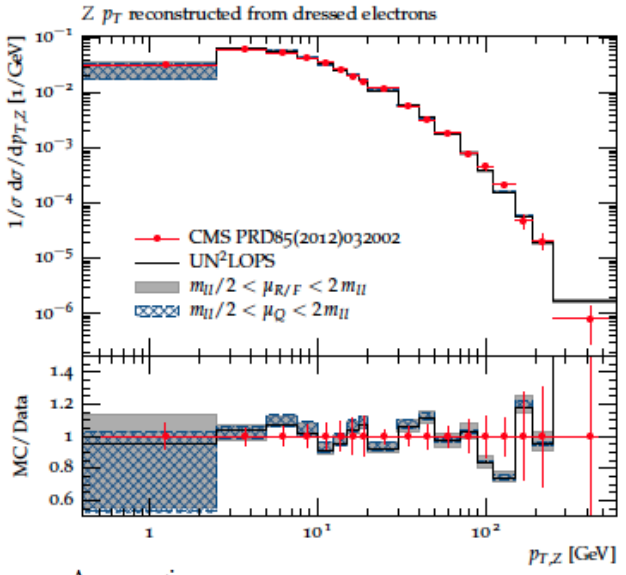
**NNLO+PS established in 2 → 1 processes:**

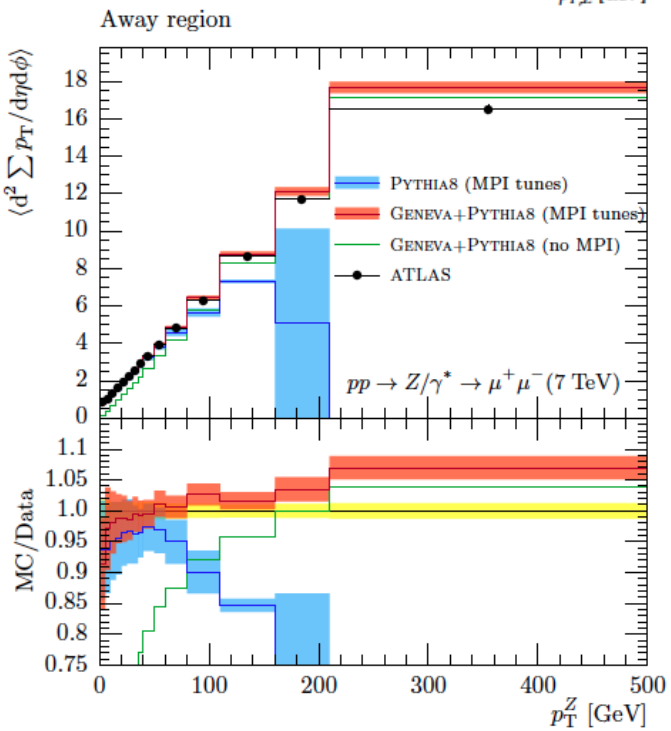
**→ UNNLOPS**
**→ MINLO**
**→ Geneva**

**Coloured final states?**

**[Alioli]**



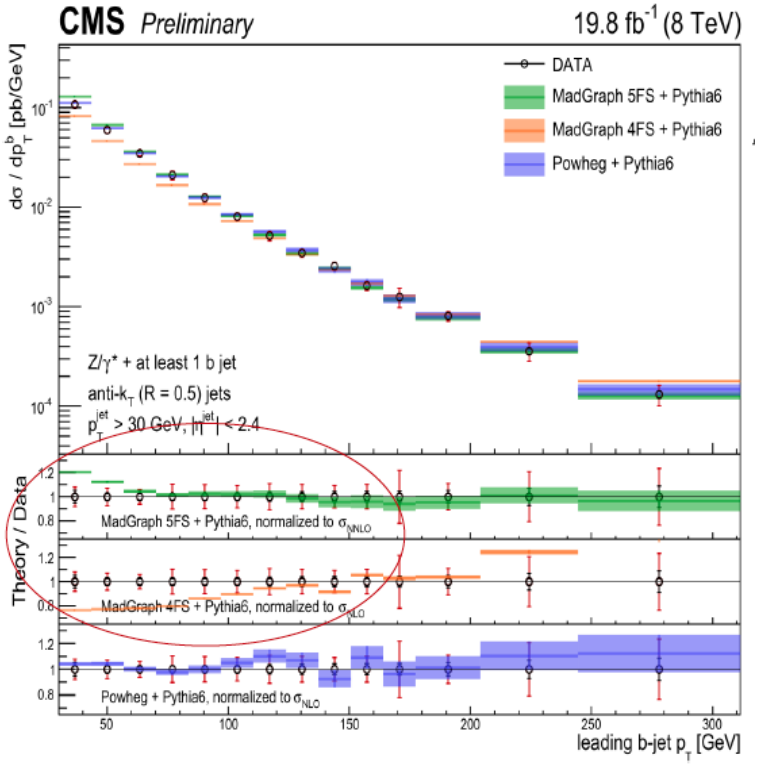



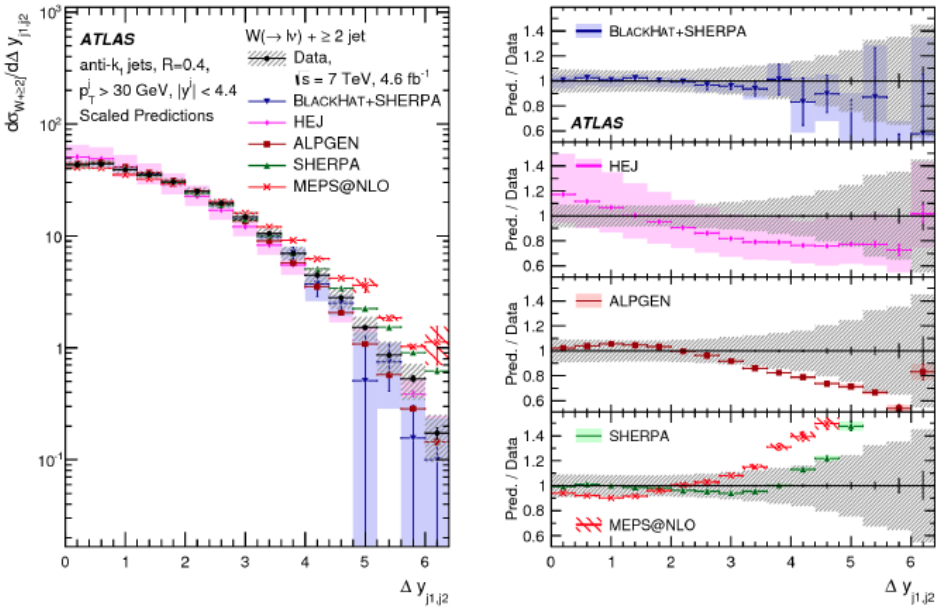
# Jets

# V's and Jets

[Sandhoff – ATLAS]

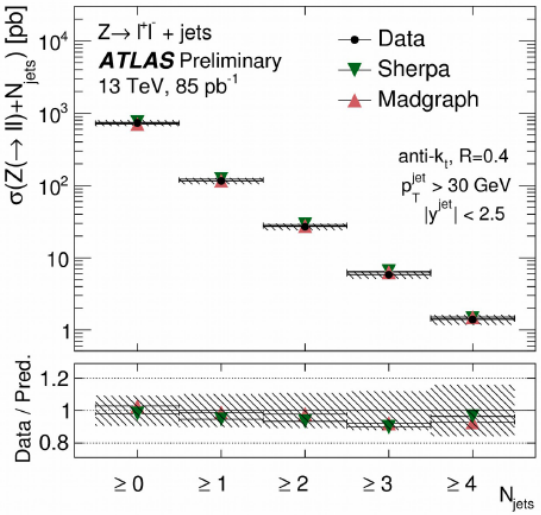
[Zhang – CMS]




Loads of data:

W/Z + jets
W/Z + b jets
Gamma + jets

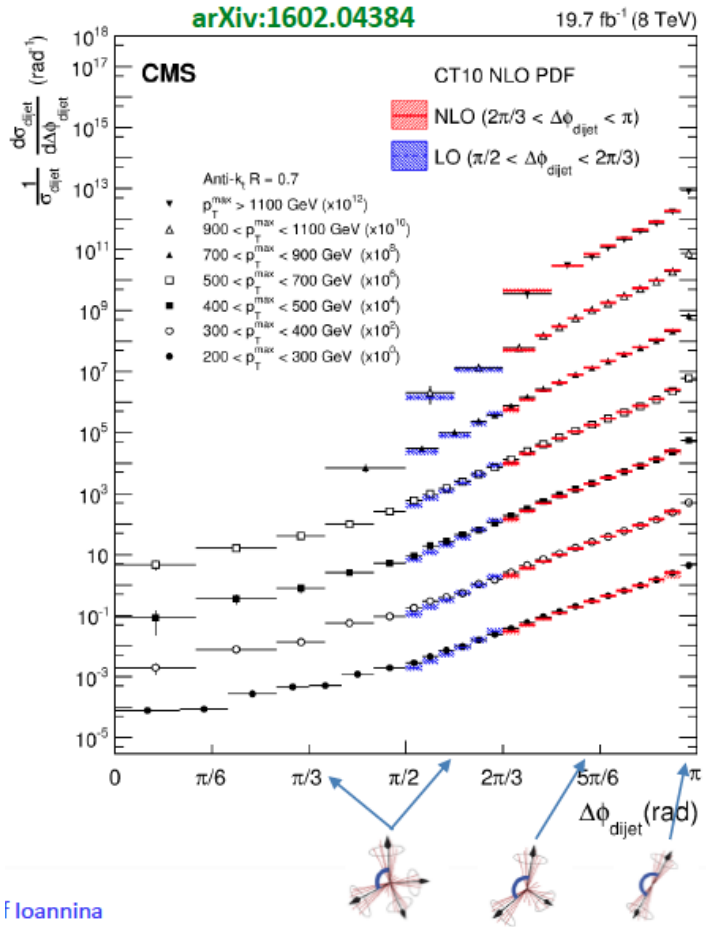



8 TeV and 13 TeV data by ATLAS & CMS.
Challenges multijet predictions.

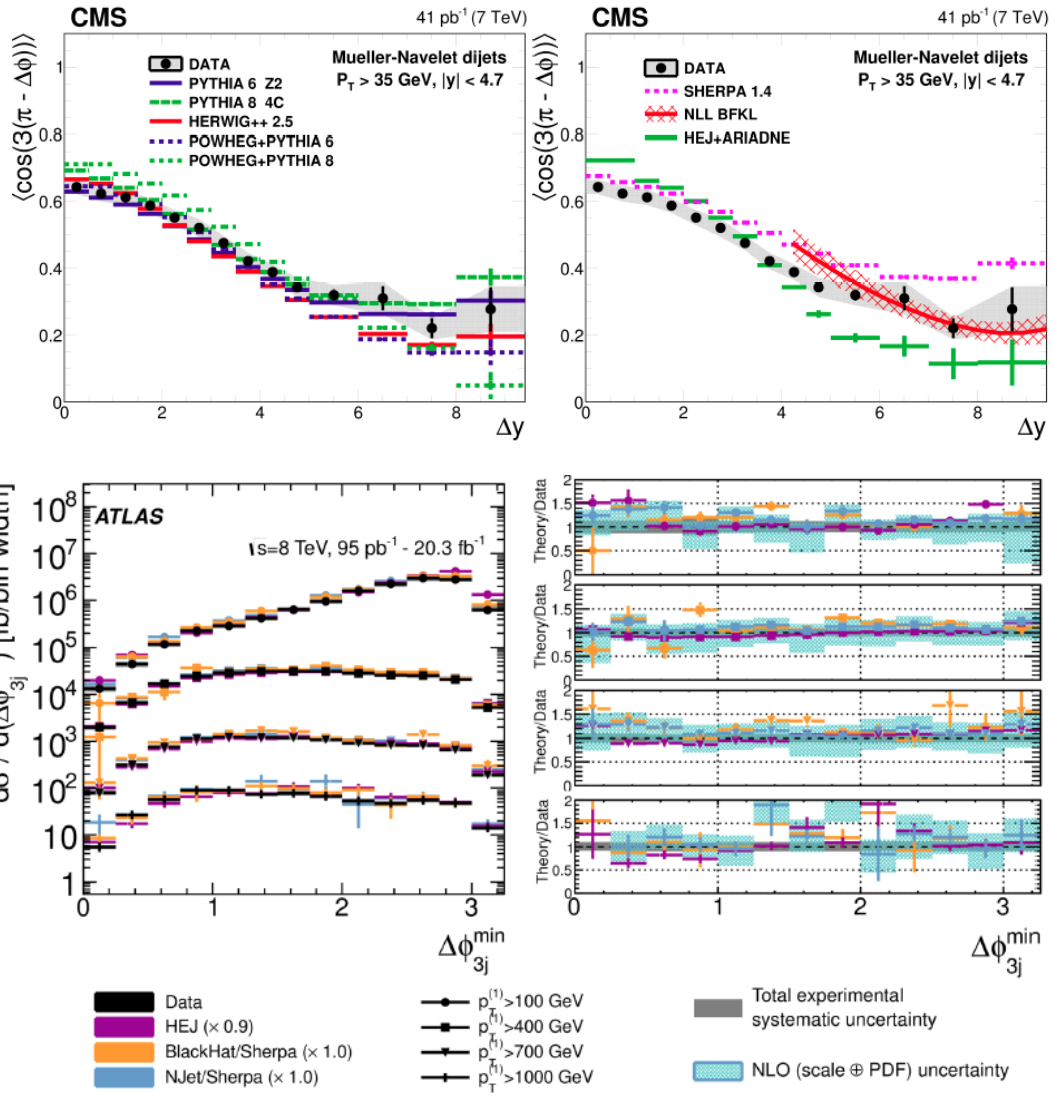
# More Jets: Mueller-Navelet, azimuthal decorrelations

[Veres – CMS]

[Kokkas – CMS]




Ioannina



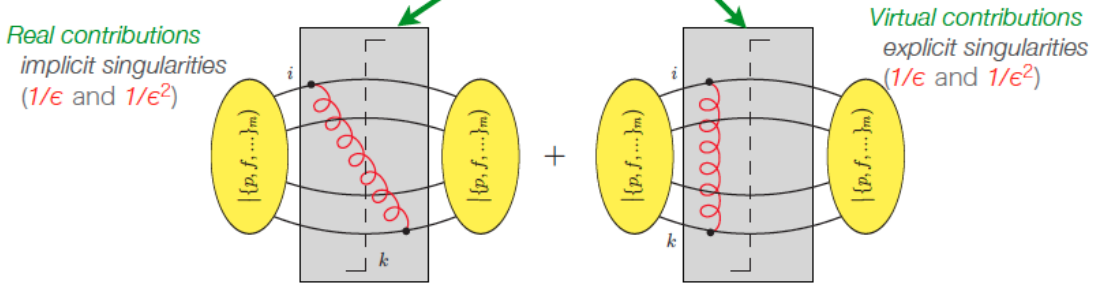

[Ridel – ATLAS]

# Evolving Jets

[Nagy]

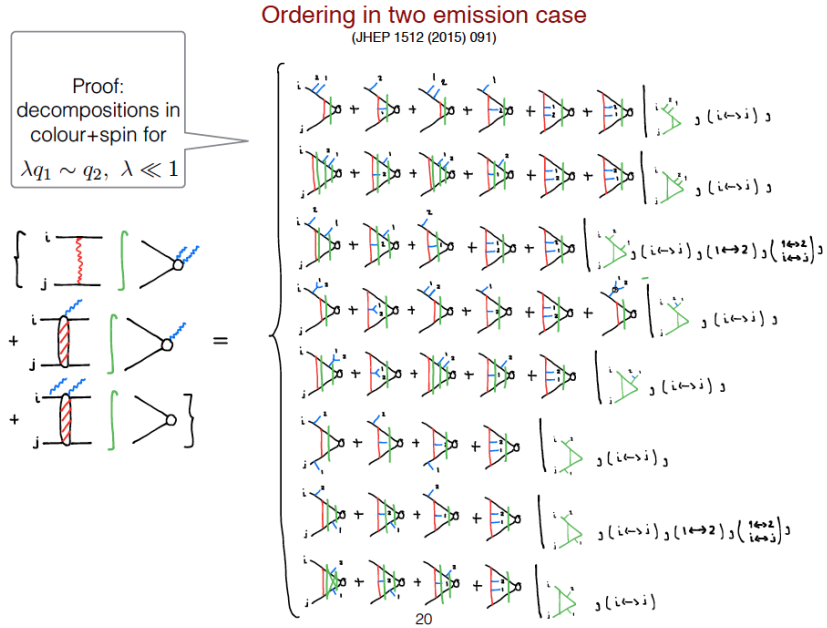
Conceptual framework for parton showers.
Contemporary MC can be formally expressed using this framework.
Threshold logarithms can be incorporated.

$$\mathcal{D}(\mu^2) = 1 + \frac{\alpha_s(\mu^2)}{2\pi}\left[\mathcal{H}_R(\mu^2) + \mathcal{H}_V(\mu^2)\right] + \cdots$$

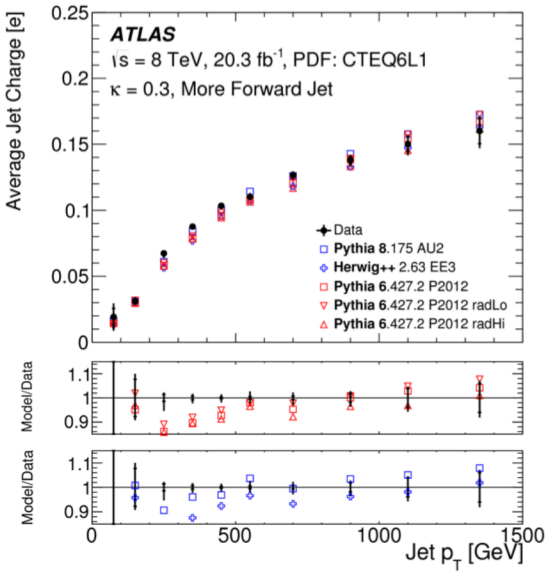


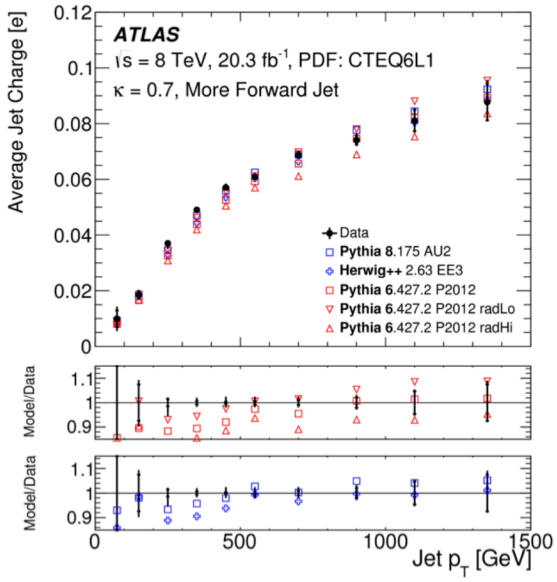

Can confirm pt ordering assumption by explicit calculation.
Coloumb gluons in parton showers?

[Angeles]



# Jet Charge & Fragmentation Functions




Jet charge measurement.
Can constrain MC parameters.

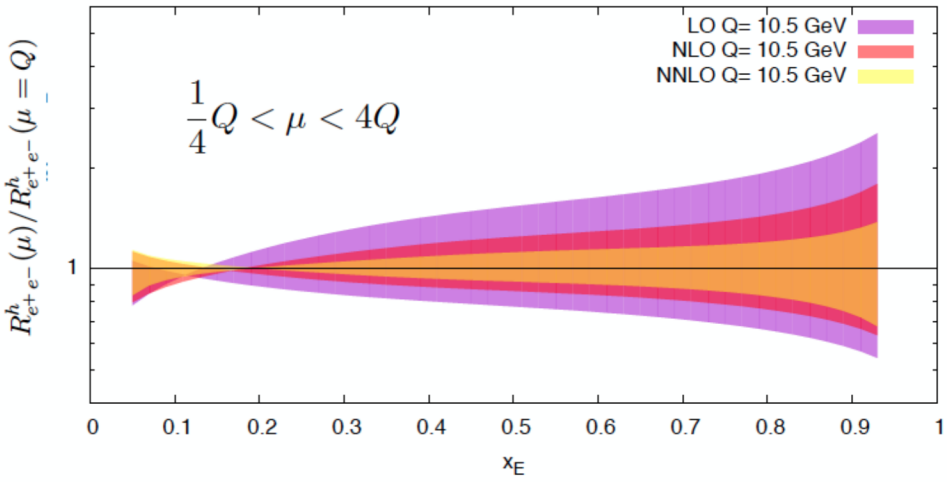
$$Q_J = \frac{1}{\left(p_{T,J}\right)^{\kappa}} \sum_{i \in Tracks} q_i \times \left(p_{T,i}\right)^{\kappa}$$

[Beacuchemin – ATLAS]

Fragmentation function evolution beyond NLO

Global NNLO fit, will include small-z resummation.

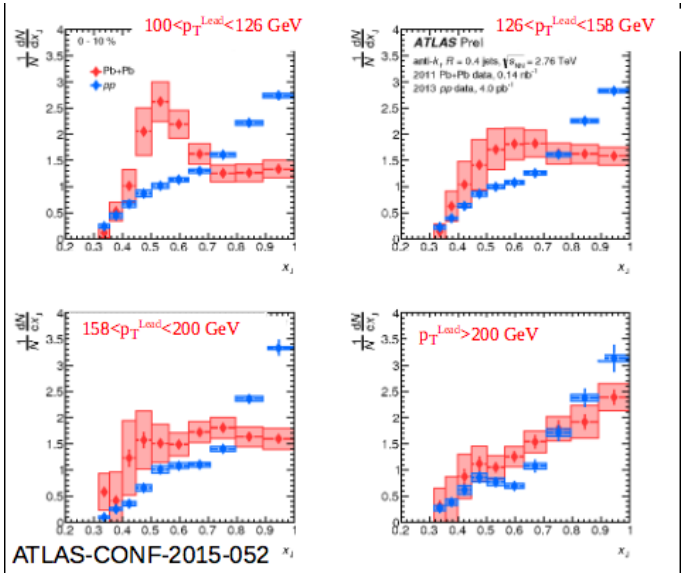
[Anderle]



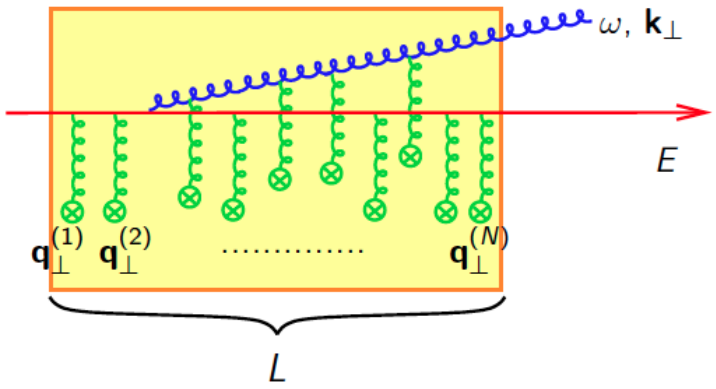
# Jets in Heavy Ions

[Santos – ATLAS]

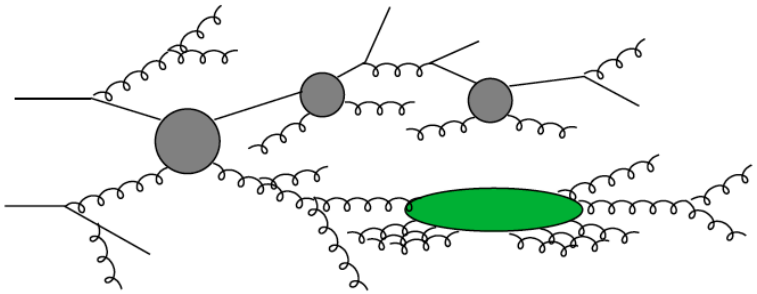
Observe jet quenching using dijet asymmetry.



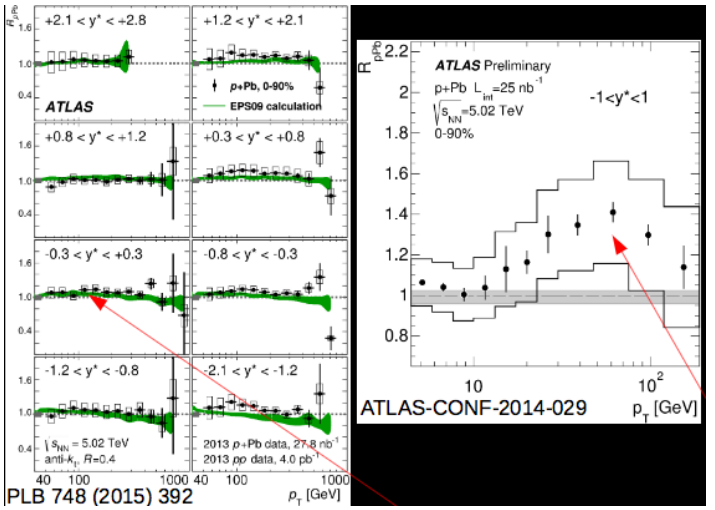

Modeling of jet quenching.




JEWEL Monte Carlo

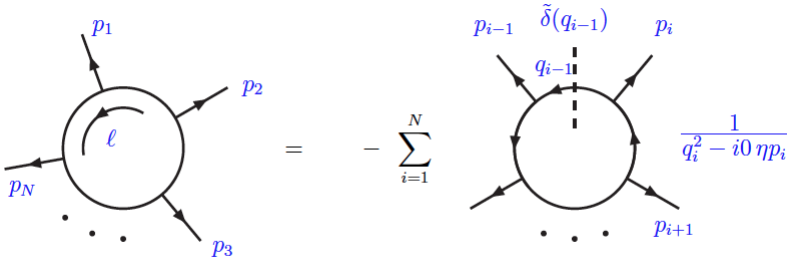


[Zapp]

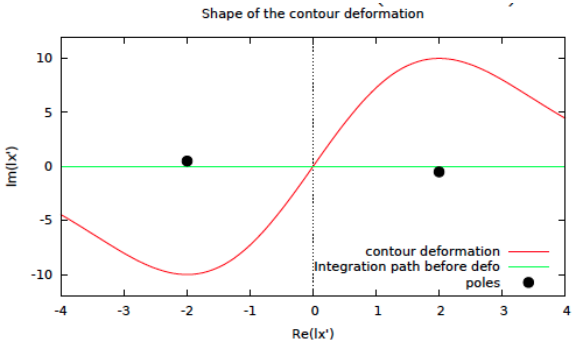


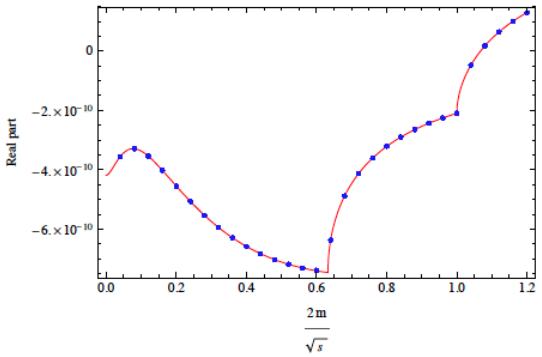

Relative yields to pp: Different for jets and hadrons.

# Precision Jets

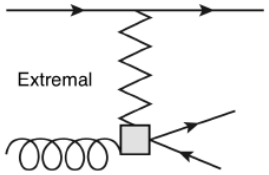


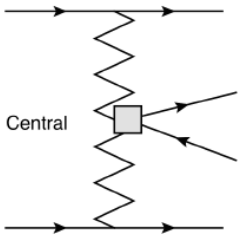

Multileg one-loop amplitudes using loop-tree duality.




[Chachamis]



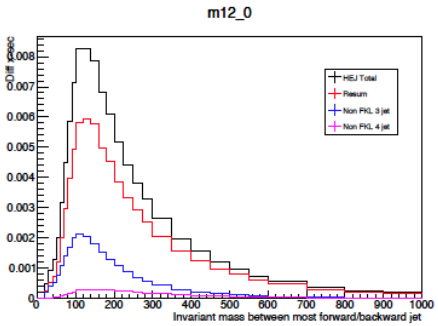



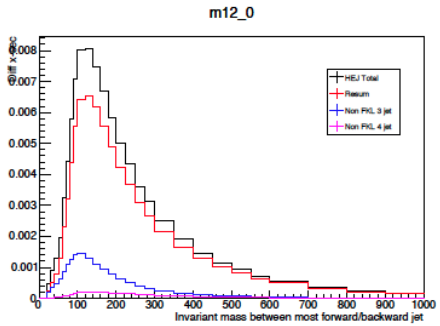

$$M_{qg\to qQQ} \sim \frac{\langle 1|\mu|a\rangle\, V^{\mu\nu}\varepsilon_\nu(p_b)}{t_1}$$

$$M_{qQ\to qq'\bar{q}'Q} \sim \frac{\langle 1|\mu|a\rangle\, V^{\mu\nu}\,\langle 4|\nu|b\rangle}{t_1 t_3}$$

[Cockburn]

Push HEJ method to NLL BFKL.



# NLO Multijet Merging

## [Bellm]

**NLO multijet merging matured.**

**NLO conveniently in most of the event generators.**

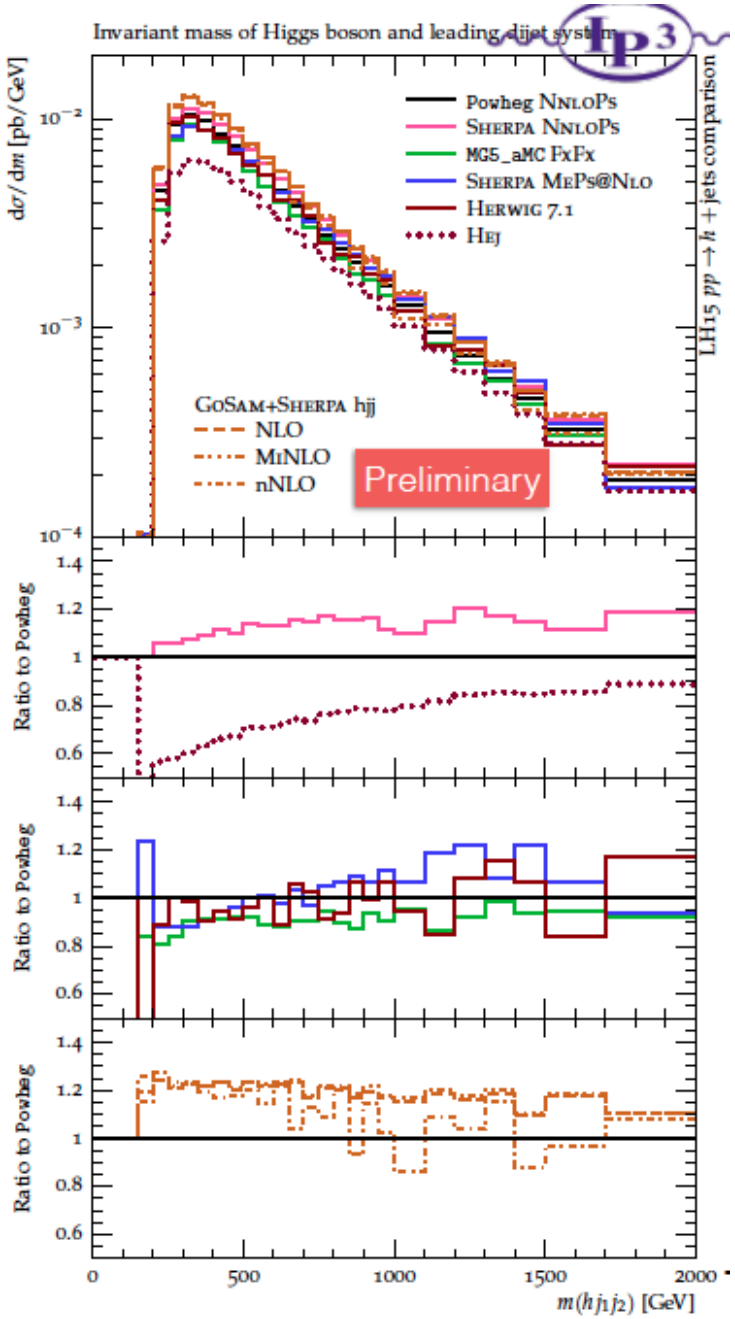
**Comparative studies including state-of-the-art predictions underway.**

$$PS[d\sigma^{merged}] = PS_0^V[d\sigma^0\Delta_\mu^0] + PS_1^V[d\sigma^1\Delta_1^0\Delta_\mu^1] + PS_2[d\sigma^2\Delta_1^0\Delta_2^1\Delta_\mu^1]$$

$$\Delta_\mu^0 = 1 - \int d\phi_1 P(z) + \mathcal{O}(\alpha_S^2)$$

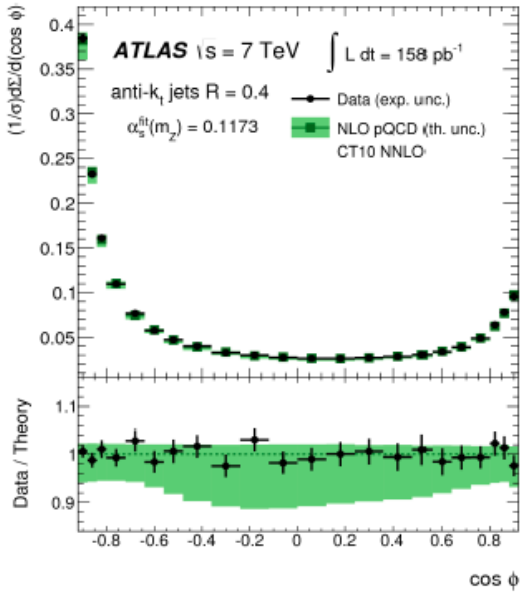
$$PS[d\sigma^{matched}] = PS_0[d\sigma^{LO}] + PS_0[d\sigma^V + \int d\phi_1 P(z) d\sigma^{LO}] + PS_1[d\sigma^R - d\phi_1 P(z) d\sigma^{LO}]$$

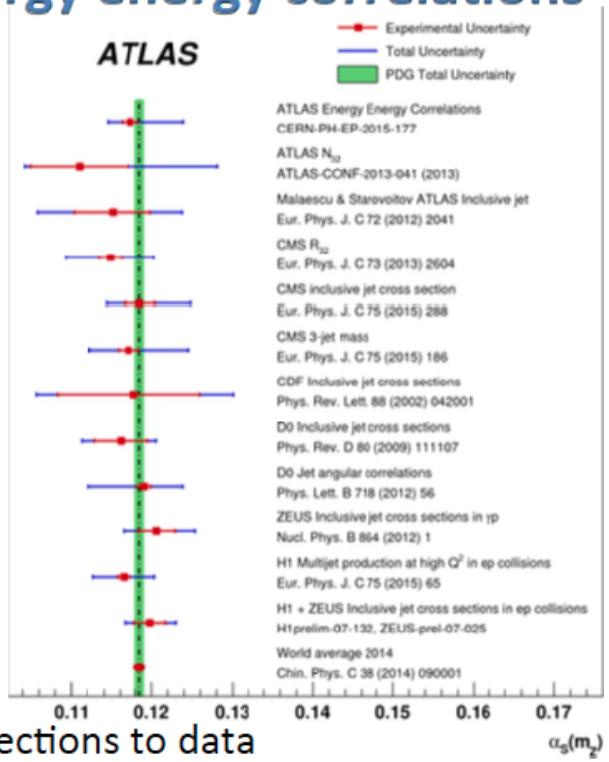
$$d\sigma^1 = d\sigma^R + \mathcal{O}(\alpha_S^2)$$



# Event Shapes & The Strong Coupling [Ridel]

## $\alpha_s$ measurement from transverse energy energy correlations



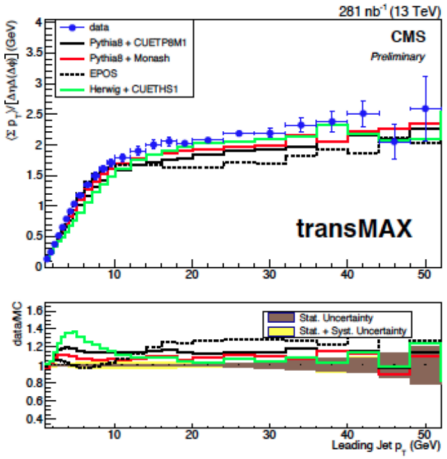

- Good agreement with the results of a $\chi^2$ fit to NLO pQCD calculations including non perturbative corrections to data
  → extraction of $\alpha_s(m_Z)$
- Small sensitivity to non-perturbative effects
- Very good experimental precision
- Result: $\alpha_s(m_Z) = 0.1173 \pm 0.0010(\text{exp.})\ ^{+0.0063}_{-0.0020}(\text{scale}) \pm 0.0017(\text{PDF}) \pm 0.0002(\text{NPC})$
- Theoretical scale uncertainty dominates over experimental uncertainties
- Excellent compatibility with World average

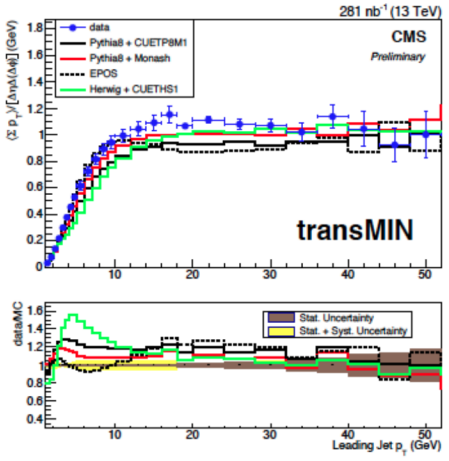
# More scatterings, please!

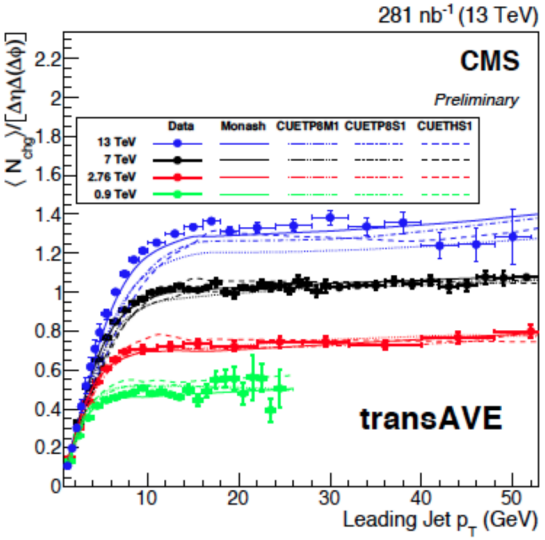
# Underlying Event

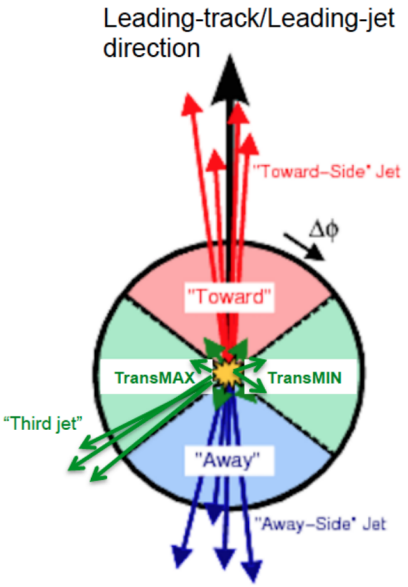
[Milstead – ATLAS]

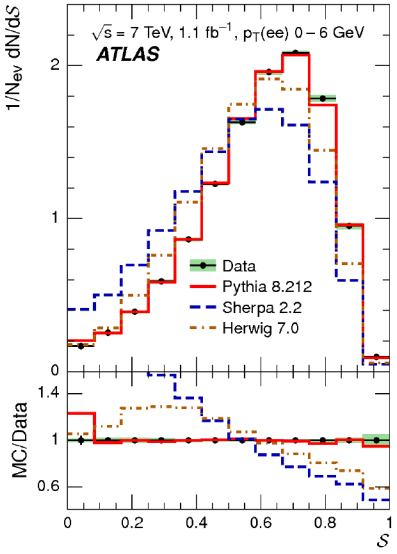
## [Solano – CMS]

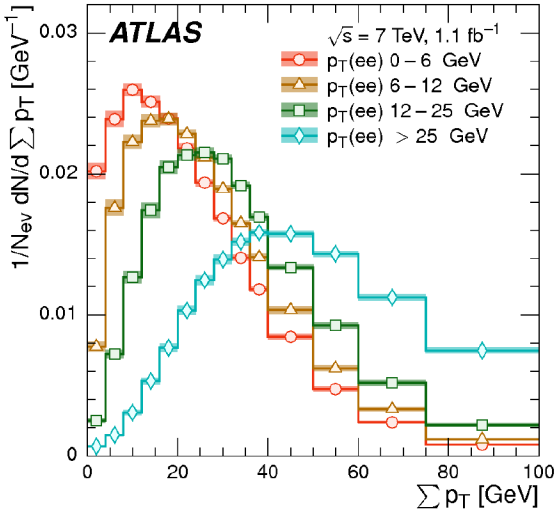


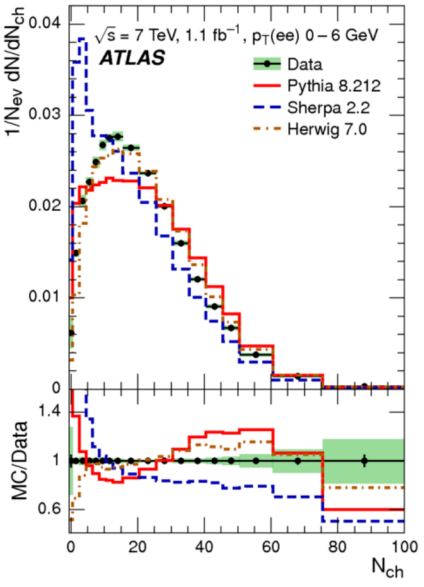



# Measuring Double Parton Scattering

| channel | data | SPS | DPS(n=0) | DPS(n=2) | DPS(n=3) |
|---|---|---|---|---|---|
| $Z^0D^0$ | 2.50 | 0.6 | 2.4 | 1.15 | 0.95 |
| $Z^0D^+$ | 0.44 | 0.25 | 0.95 | 0.5 | 0.4 |
| sum | 2.94 | 0.85 | 3.35 | 1.65 | 1.35 |

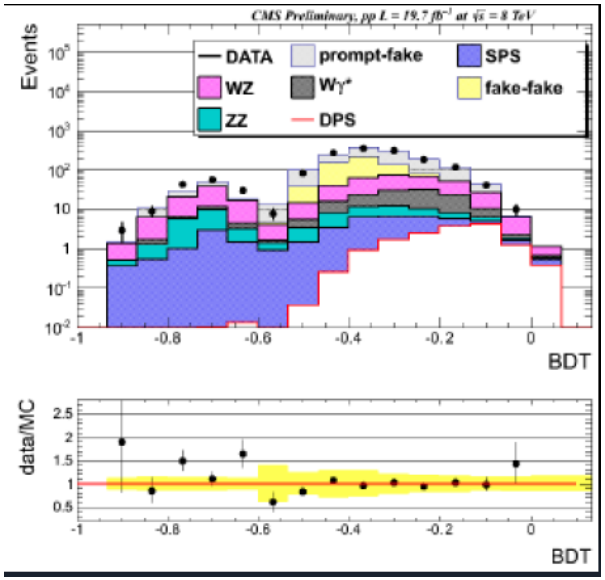
The data are taken from [LHCb Collab., JHEP 1401, 091 (2014)].

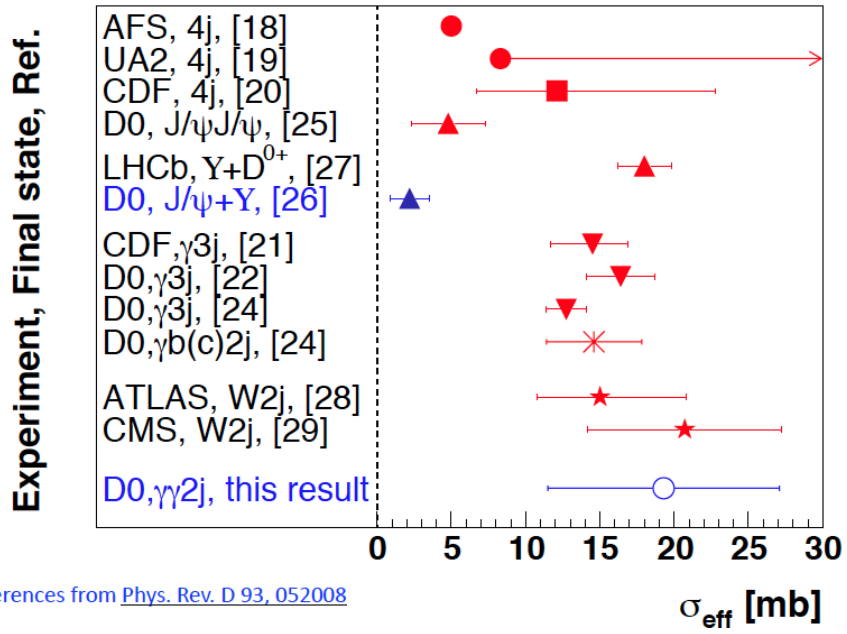
DPS opportunities for LHCb

[Malyshev]

Extract sigma effective – model dependence?

[Alves – CMS]




References from Phys. Rev. D 93, 052008

[Bertram -D0]

CMS trying gamma+3 jets, same-sign W, …

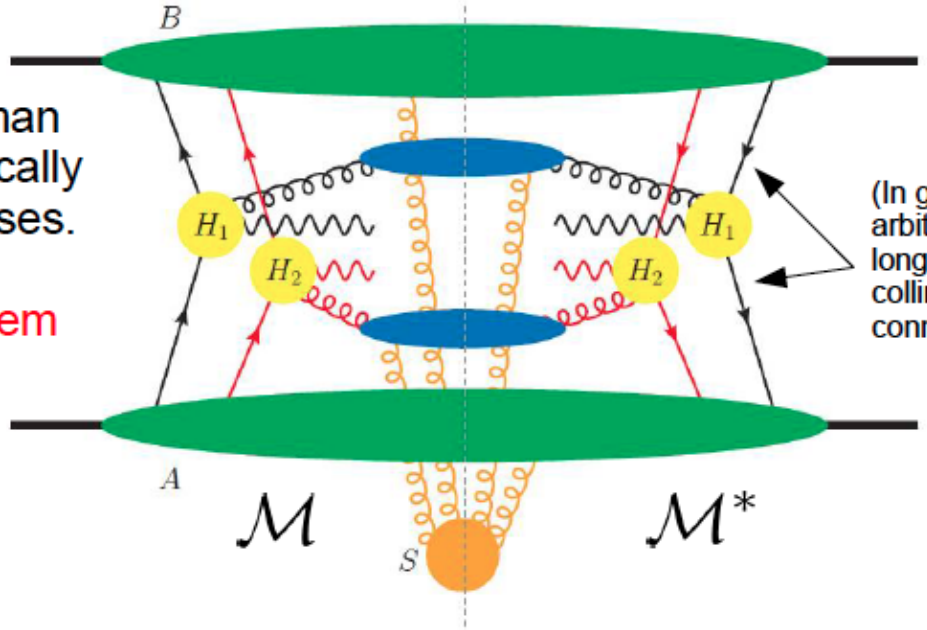
# DPS: Towards a Factorization Theorem

[Gaunt]

**Major project underway to establish factorization theorem for DPS.**
**Crucial ingredient: Cancellation of Glauber exchanges.**
**Shown for double Drell-Yan at all orders.**

Pinch singularities in Feynman graphs correspond to physically (classically) allowed processes.

Coleman-Norton theorem




(In general, also arbitrarily many longitudinally polarised collinear gluon connections to hard)

# DPS: Kt Factorization Development

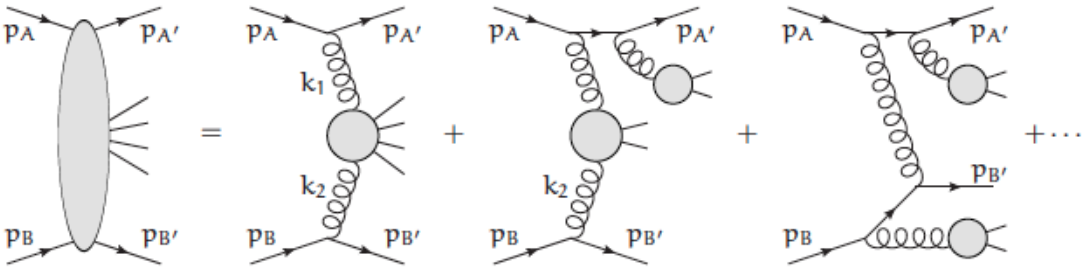
[Serino, Maciula]

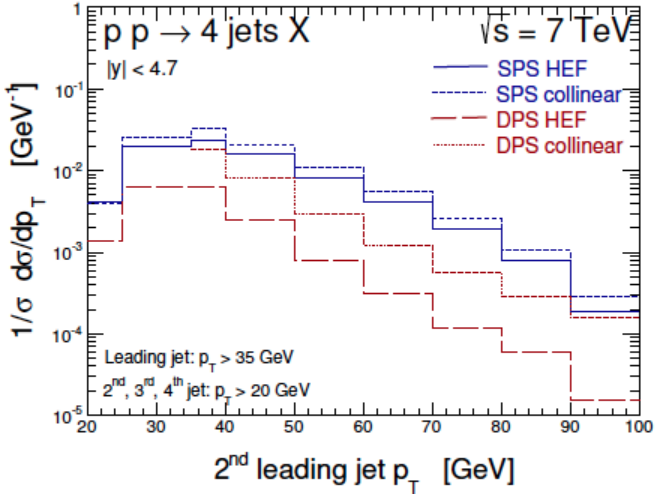
New developments in automating off-shell amplitudes.

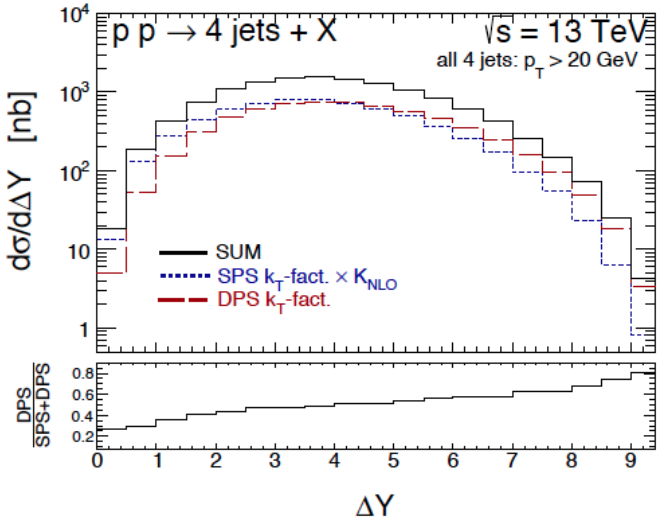
Start analyzing DPS using kt factorization.

Can describe four-jet data at 7 & 8 TeV.

More observables to pin down DPS contribution suggested.



# Thanks!

... to the organizers for the interesting and nice conference.