QCD and Monte Carlo simulation VI

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http://www.desy.de/~jung/qcd_and_mc_2015/

Outline of the lectures

- 12. Oct   Intro to Monte Carlo techniques and structure of matter
- 13. Oct   DGLAP: solution with MCs
- 26. Oct DGLAP/BFKL/CCFM: evolution for small x
- 27. Oct DGLAP/BFKL/CCFM: evolution for small x
- 16. NovW/Z production in pp and soft gluon resummation
- 19. Nov   Multiparton interactions & latest LHC results: small x, multiparton interactions, QCD in high luminosity phase: Higgs as a gluon trigger
- Exercises
- 14 & 15 Oct
- 28 & 29 Oct
- 17 & 18 Nov

Recap of last lecture

From DY to $pp \rightarrow jets$

Jet production in pp

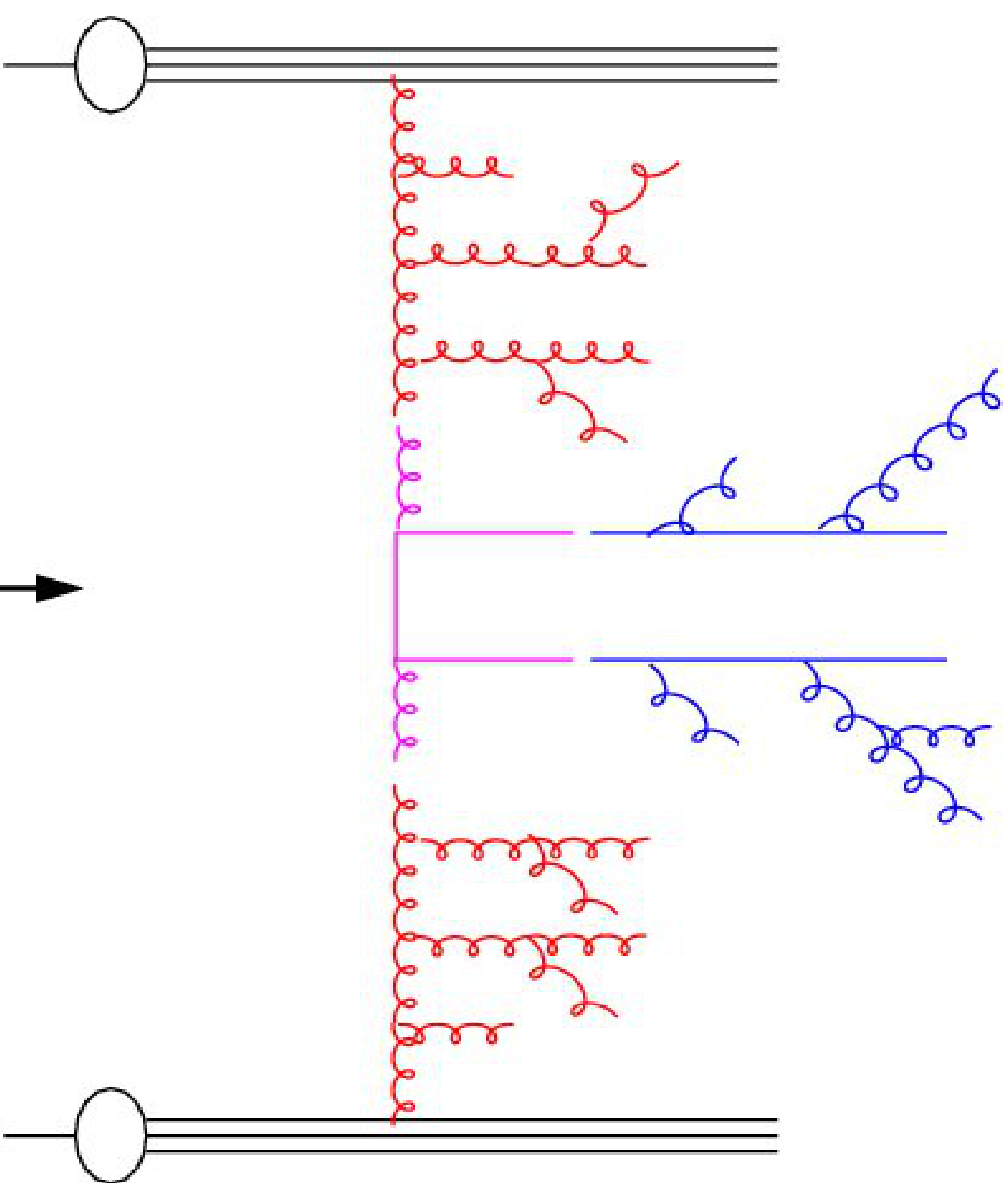
- x-section (i.e. for light and heavy quarks ($t\bar{t}$) production)

$$\sigma(\mathrm{pp} \to \mathrm{q\bar{q}X}) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} x_1 G(x_1,\bar{q}) x_2 G(x_2,\bar{q}) \times \hat{\sigma}(\hat{s},\bar{q})$$

- with gluon densities $xG(x,\bar{q})$

- hard x-section:

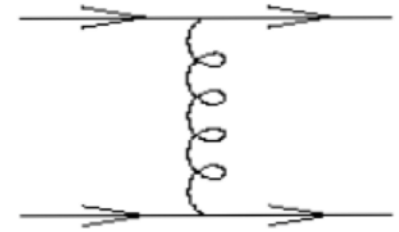
$$\frac{d\sigma}{dt} = \frac{1}{64\hat{s}^2}|M_{ij}|^2 \longrightarrow$$



Lowest Order Diagrams

Ellis, Stirling, Webber
QCD & collider physics p248

$qq' \to qq'$

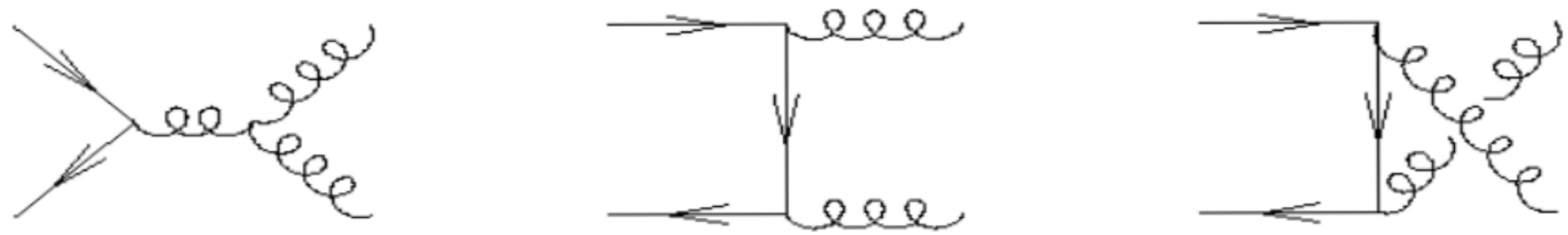


(a)

$qq \to qq$

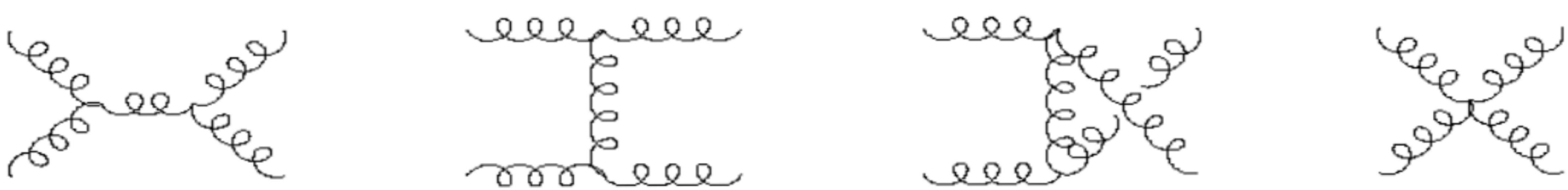
(b)

$q\bar{q} \to gg$



(c)

$gg \to gg$



(d)

$2 \to 2$ processes

invariant matrix elements for $2 \to 2$ processes with massless partons

Ellis, Stirling, Webber
QCD & collider physics p249

Process	$\bar{\sum}\lvert\mathcal{M}\rvert^2/g^4$	$\theta^* = \pi/2$
$qq' \to qq'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.22
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.26
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.22
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.59
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	1.04
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.15
$gq \to gq$	$-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$	30.4

Remember: W+jet and dijets

- check on propagator:

CDF Collaboration (F. Abe et al.).Phys.Rev.Lett.73:2296-2300,1994.

Ellis, Stirling, Webber
QCD & collider physics p248

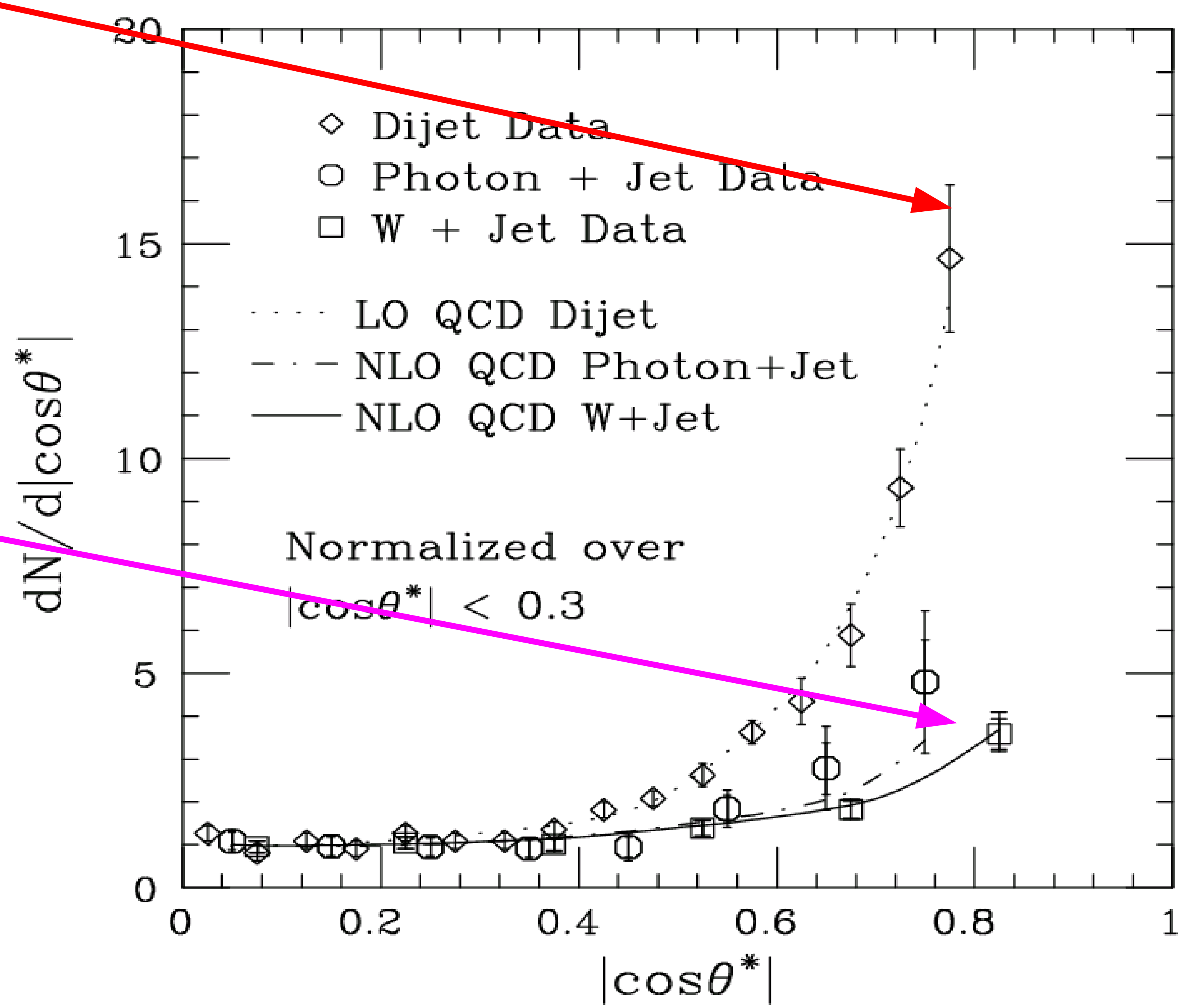
$$qq \to qq$$

$$|M|^2 \sim \frac{s^2+u^2}{t^2}$$

$$\sim \frac{1}{t^2} \sim \frac{1}{(1-cos\theta^*)^2}$$

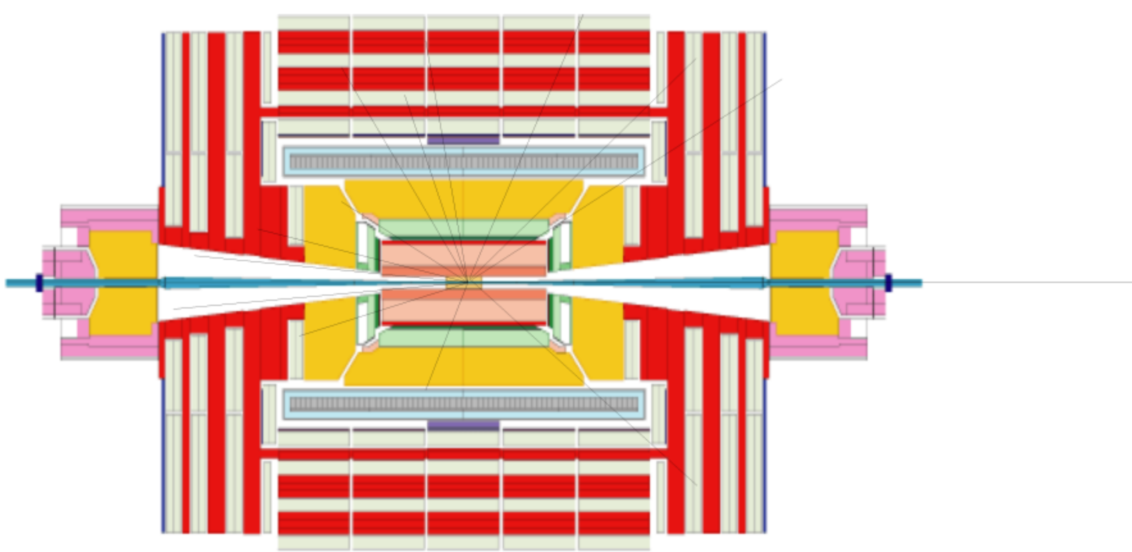
$$qq \to W + g:$$

$$|M|^2 \sim \frac{1}{t} \sim \frac{1}{(1-cos\theta^*)}$$

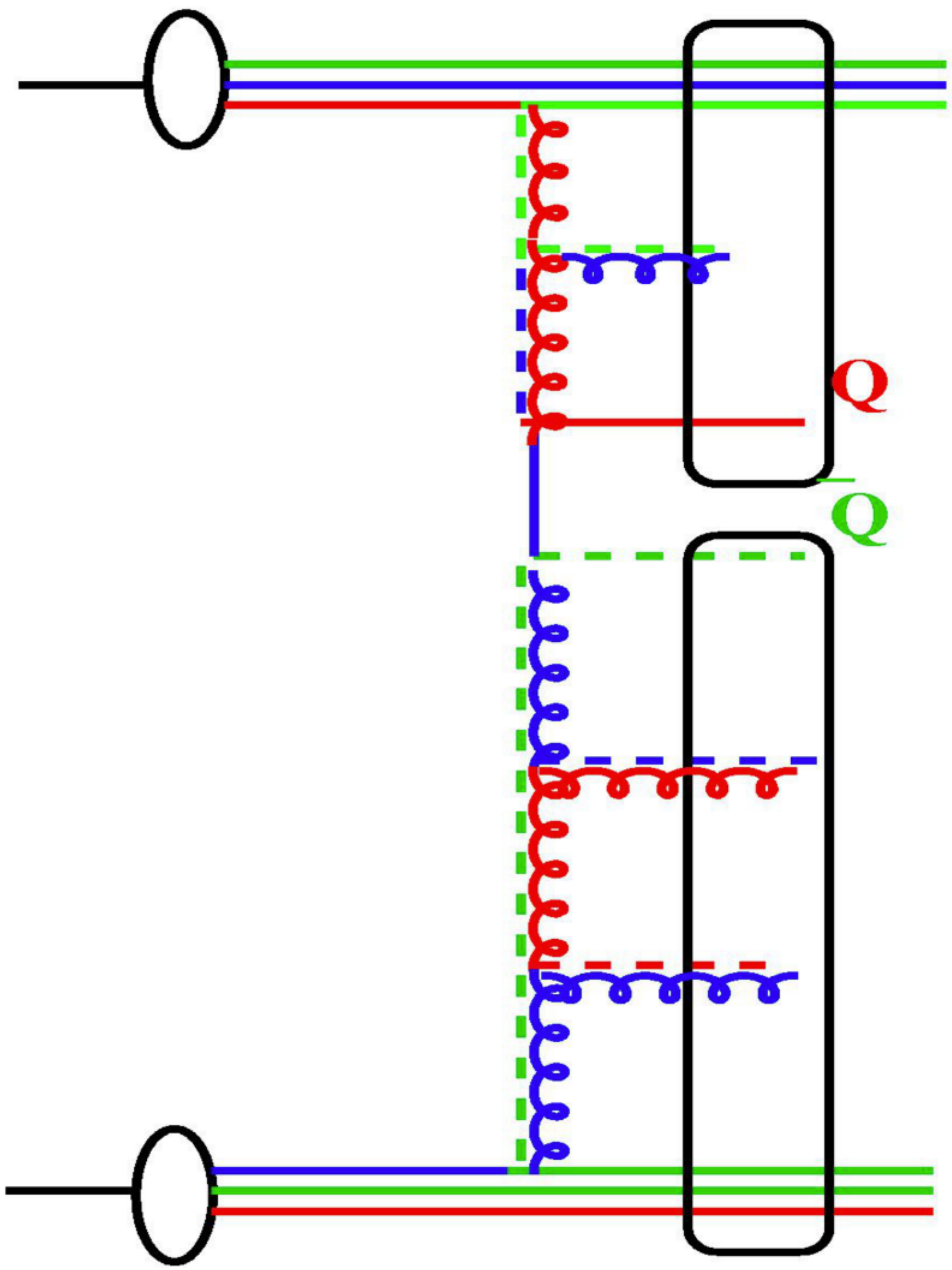


Color Flow in pp

- quarks carry color
- anti-quarks carry anti-color
- gluons carry color – anti-color
    - connect to color singlet systems
    - watch out pp or $p\bar{p}$



$$pp \to q\bar{q} + X$$

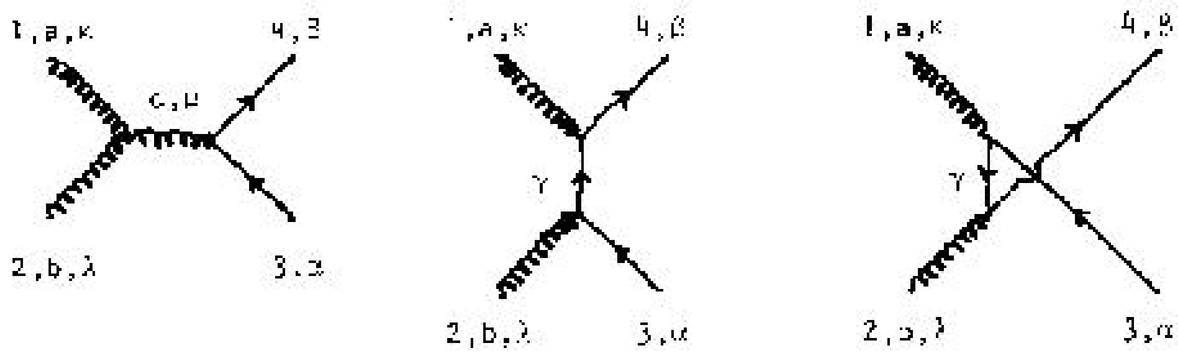


Color Flow in pp

The Lund Monte Carlo For High P(T) Physics H.U. Bengtsson
Comput.Phys.Commun.31:323,1984.

Process: $gg \to q_i \bar{q}_i$

Diagrams:



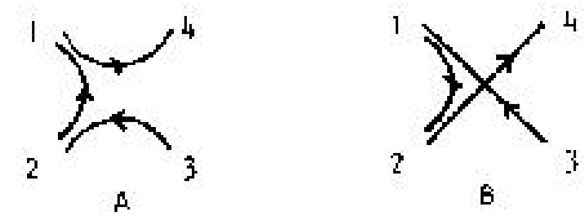
Amplitudes:

s: $g^2 f^{abc} T^c_{\alpha\beta} \bar{u}_i^\beta(q_4) \frac{\epsilon_1^\kappa \epsilon_2^\lambda \gamma^\mu}{\hat{s}} C_{\kappa\lambda\mu}(q_1, q_2, -q_1 - q_2) v_i^\alpha(q_3)$

t: $-ig^2 T^b_{\alpha\gamma} T^a_{\gamma\beta} \bar{u}_i^\beta(q_4) \not\epsilon_1 \frac{\not q_1 - \not q_4}{\hat{t}} \not\epsilon_2 v_i^\alpha(q_3)$

u: $-ig^2 T^a_{\alpha\gamma} T^b_{\gamma\beta} \bar{u}_i^\beta(q_4) \not\epsilon_2 \frac{\not q_1 - \not q_3}{\hat{u}} \not\epsilon_1 v_i^\alpha(q_3)$

Colour flows:



String configurations:

Colour factors: A: $T^b_{\alpha\gamma} T^a_{\gamma\beta}$; B: $T^a_{\alpha\gamma} T^b_{\gamma\beta}$

Amplitudes:

A: $-ig^2 \bar{u}_i^\beta(q_4) \left[\not\epsilon_1 \frac{\not q_1 - \not q_4}{\hat{t}} \not\epsilon_2 - \frac{\epsilon_1^\kappa \epsilon_2^\lambda \gamma^\mu}{\hat{s}} C_{\kappa\lambda\mu}(q_1, q_2, -q_1 - q_2) \right] v_i^\alpha(q_3)$

B: $-ig^2 \bar{u}_i^\beta(q_4) \left[\not\epsilon_2 \frac{\not q_1 - \not q_3}{\hat{u}} \not\epsilon_1 + \frac{\epsilon_1^\kappa \epsilon_2^\lambda \gamma^\mu}{\hat{s}} C_{\kappa\lambda\mu}(q_1, q_2, -q_1 - q_2) \right] v_i^\alpha(q_3)$

Cross-sections:

A: $\frac{\pi \alpha_s^2}{\hat{s}^2} \frac{1}{6} \left(\frac{\hat{u}}{\hat{t}} - 2 \frac{\hat{u}^2}{\hat{s}^2} \right)$; B: $\frac{\pi \alpha_s^2}{\hat{s}^2} \frac{1}{6} \left(\frac{\hat{t}}{\hat{u}} - 2 \frac{\hat{t}^2}{\hat{s}^2} \right)$

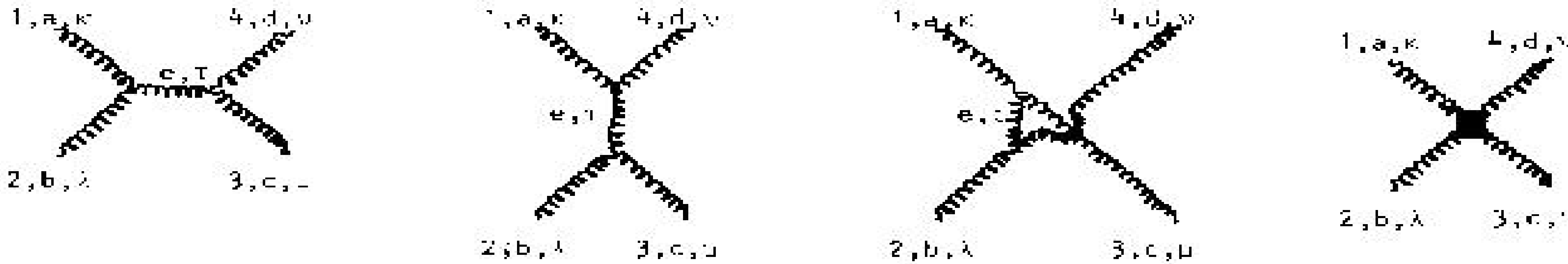
$$A + B = \ldots \left(\frac{\hat{u}}{\hat{t}} - 2 \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} + \frac{\hat{t}}{\hat{u}} \right) = \frac{\hat{u}^2 + \hat{t}^2}{\hat{t}\hat{u}} - 2 \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}$$

Color Flow in pp

The Lund Monte Carlo For High P(T) Physics H.U. Bengtsson
Comput.Phys.Commun.31:323,1984.

Process: gg → gg

Diagrams:



Amplitudes:

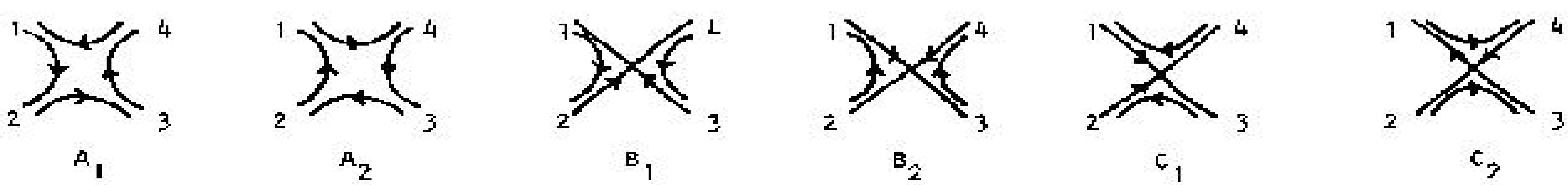
s: $-ig^2\frac{1}{\hat{s}} f^{abe}f^{cde}\epsilon_1^{\kappa}\epsilon_2^{\lambda}\epsilon_3^{\mu}\epsilon_4^{\nu}C_{\kappa\lambda\tau}(-q_1,-q_2,q_1+q_2)C_{\mu\nu}{}^{\tau}(q_3,q_4,-q_3-q_4)$

t: $-ig^2\frac{1}{\hat{t}} f^{dae}f^{bce}\epsilon_1^{\kappa}\epsilon_2^{\lambda}\epsilon_3^{\mu}\epsilon_4^{\nu}C_{\nu\kappa\tau}(q_4,-q_1,q_1-q_4)C_{\lambda\mu}{}^{\tau}(-q_2,q_3,q_2-q_3)$

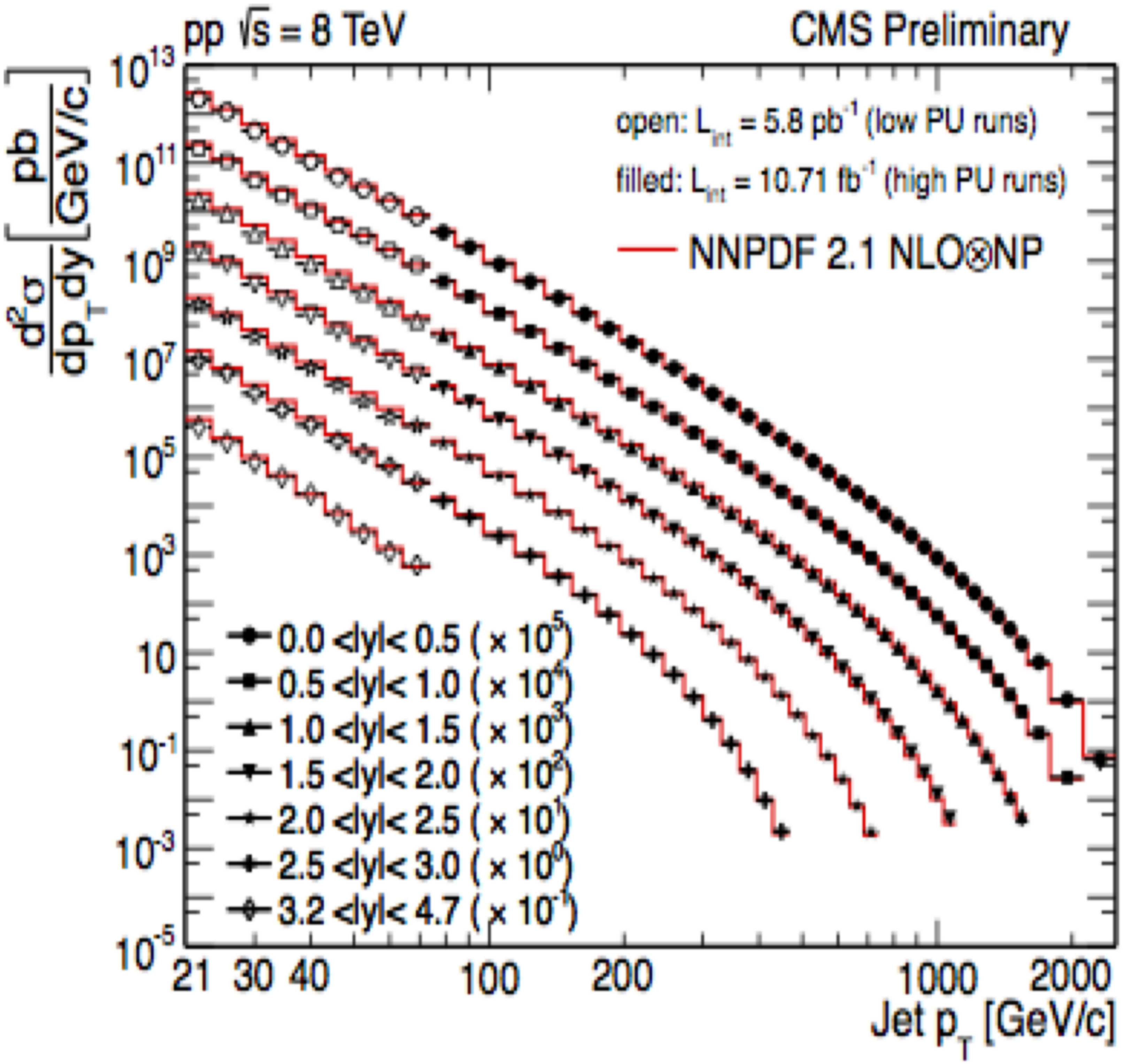
u: $-ig^2\frac{1}{\hat{u}} f^{cae}f^{bde}\epsilon_1^{\kappa}\epsilon_2^{\lambda}\epsilon_3^{\mu}\epsilon_4^{\nu}C_{\mu\kappa\tau}(q_3,-q_1,q_1-q_3)C_{\lambda\nu}{}^{\tau}(-q_2,q_4,q_2-q_4)$

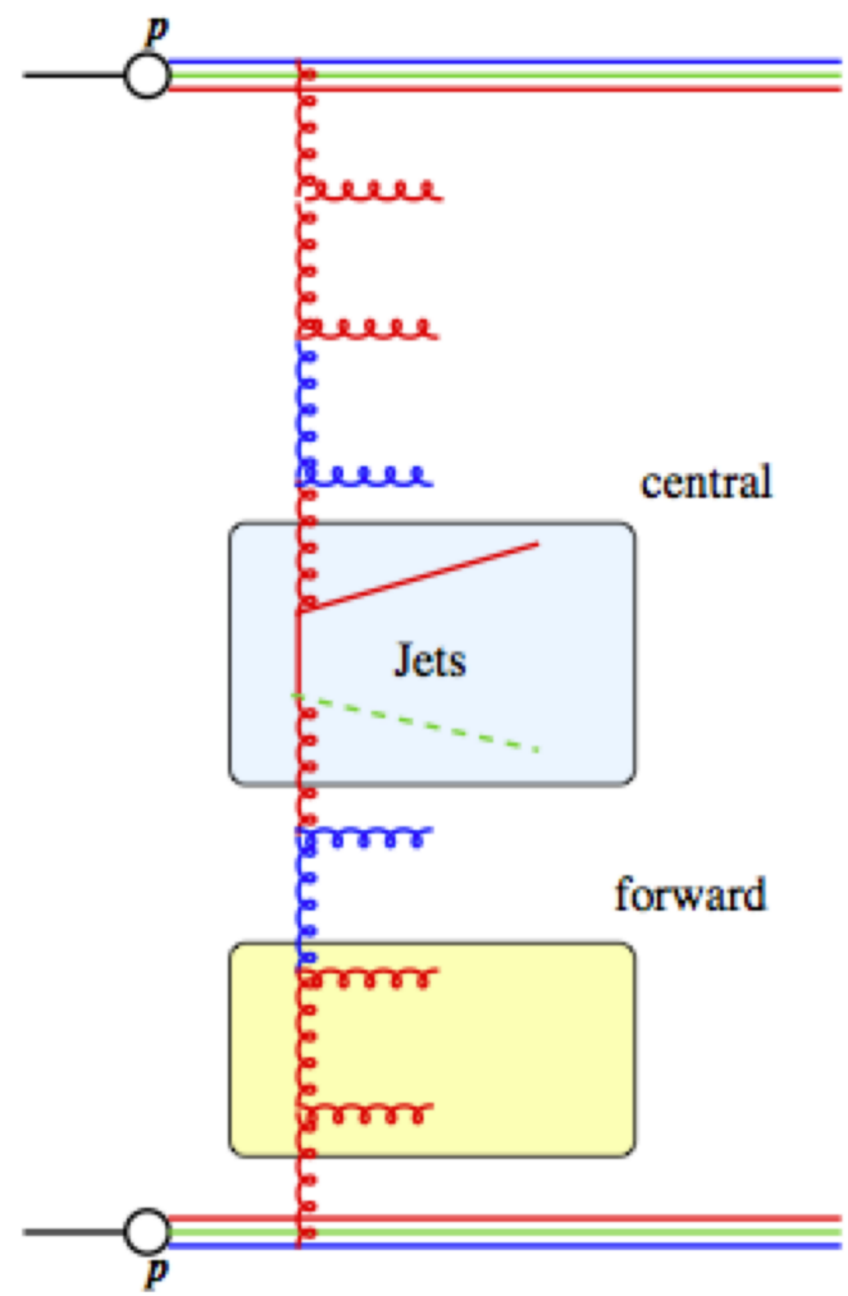
4: $-ig^2 f^{abe}f^{cde}(g_{\kappa\mu}g_{\lambda\nu}-g_{\kappa\nu}g_{\lambda\mu}) - ig^2 f^{dae}f^{bce}$
$\times(g_{\kappa\mu}g_{\lambda\nu}-g_{\kappa\lambda}g_{\nu\mu})+ig^2 f^{cae}f^{bde}(g_{\kappa\lambda}g_{\mu\nu}-g_{\kappa\nu}g_{\lambda\mu})$

Colour flows:



Jet production at the LHC





Impressive agreement of theory predictions with measurements

…

at least in some regions of phase-space

…

is there still anything left ?

Observations so far

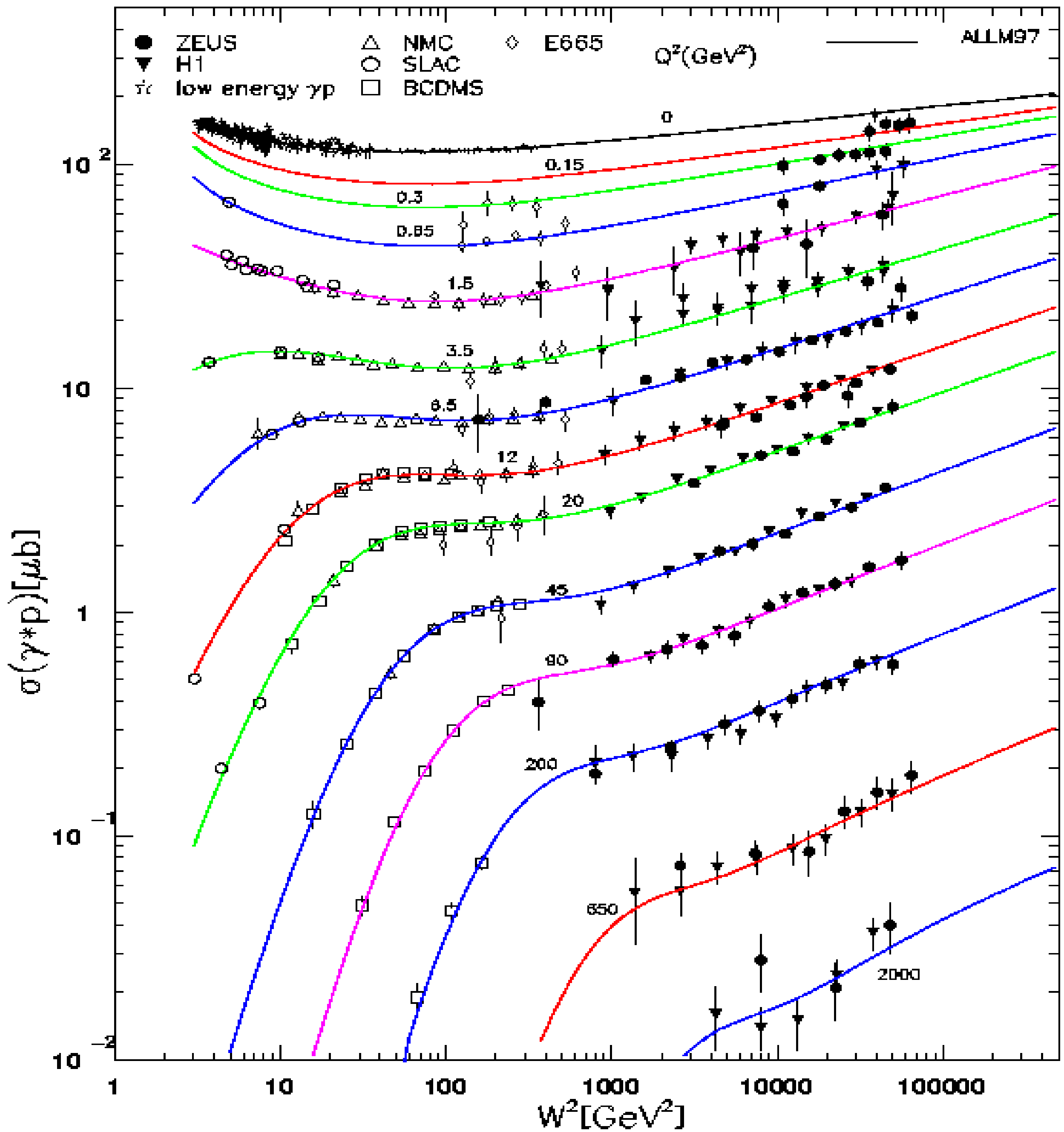
- parton densities increase at small x
  - leads to violation of unitarity
  - need saturation
    - high densities $\rightarrow$ multi-partonic interactions
    - experimental observations
  - multiparton radiation $\rightarrow$ multi-jet production

- parton densities at small x
  - require introduction of k_t
  - but effects are visible at large x
  - TMD parton densities
    - new complications
    - factorization breaking

parton densities at small x

- violation of unitarity

High energy behavior of x section



From H. Abramowicz A. Levy hep-ph/9712415

$$\sigma(\gamma^* p) = \frac{4\pi^2\alpha}{Q^2} F_2(x,Q^2) = \frac{4\pi^2\alpha}{Q^2} \sum e_q^2 x q(x,Q^2)$$

$$x = \frac{Q^2}{W^2 + Q^2}$$

- rising x-section with W^2
- at large energies can become larger than σ_{tot}
- mechanism needed which tames rise at large energies:

➔ Saturation

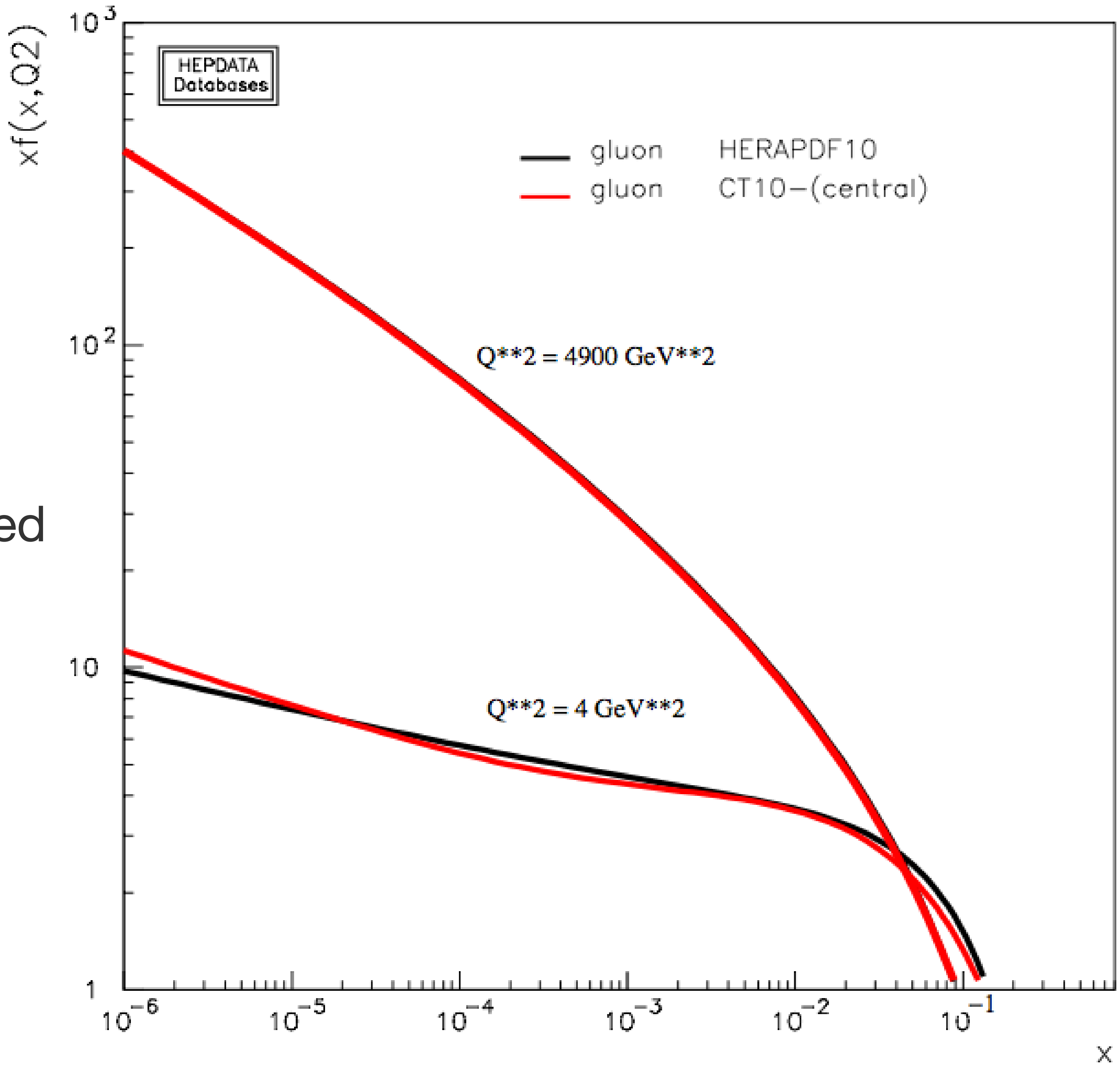
Why this happens ?

- Very high parton densities at small x
- when

$$E = xP \sim k_\perp$$

new effects in evolution appear:

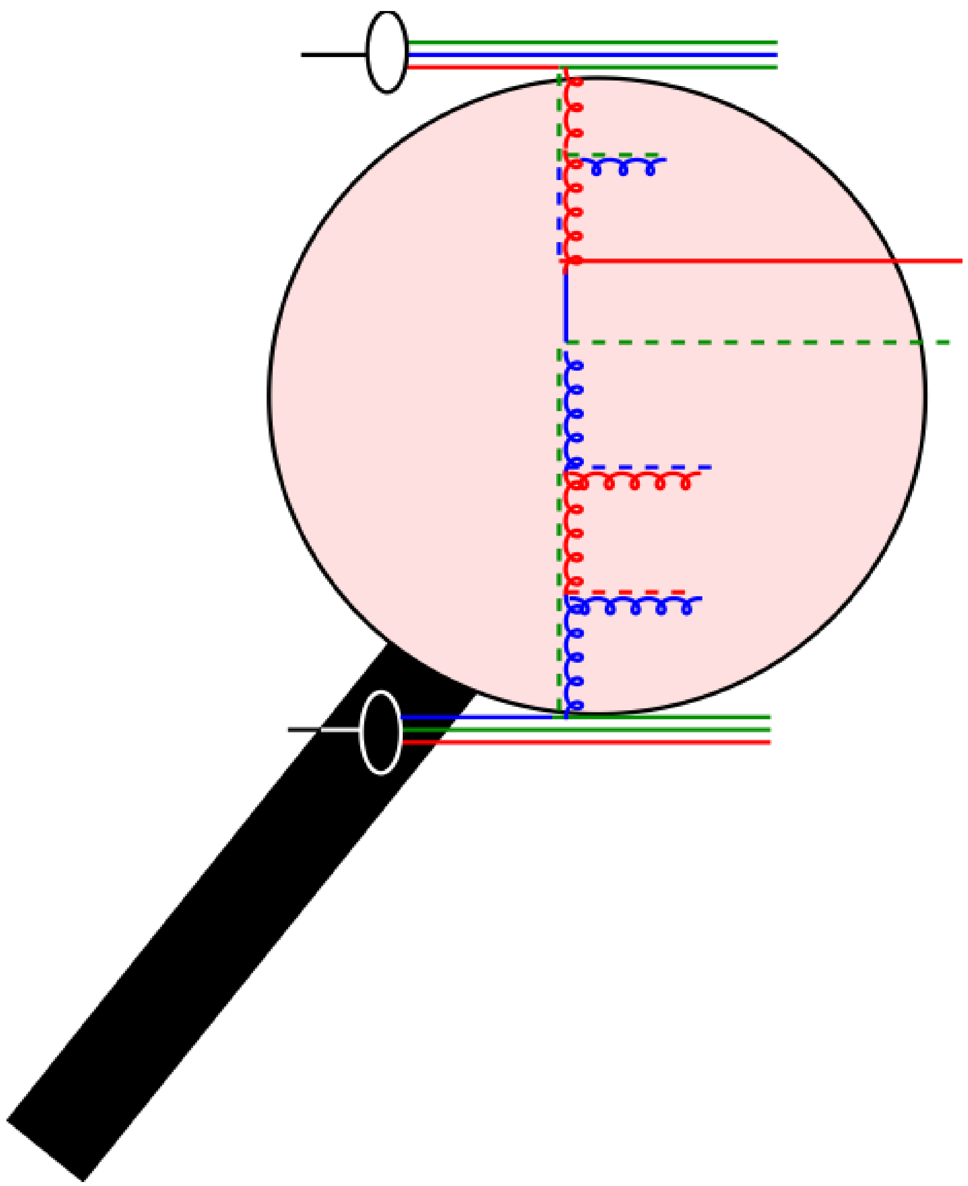
  - $k_\perp$ cannot be neglected
  - strong $k_\perp$ ordering broken
  - high energy evolution (BFKL/CCFM)



Partonic Cross sections

- Cross section

$$\sigma(p_1 + p_2 \to j_1 + j_2 + X) \quad = \quad f(x_1, \mu^2) \otimes \hat{\sigma}(x_1 p_1 + x_2 p_2 \to j_1 + j_2) \otimes f(x_2, \mu^2)$$



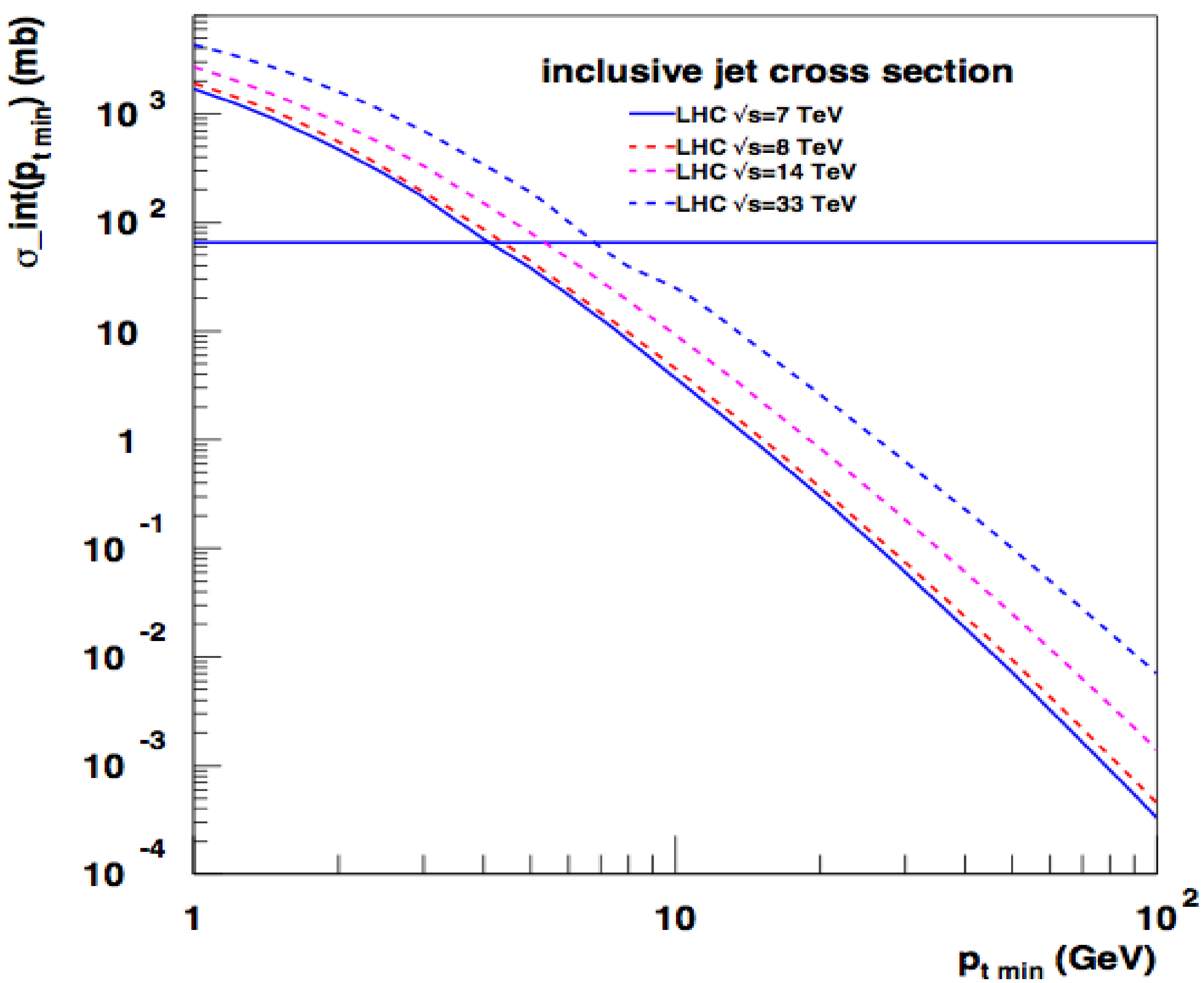
- partonic cross section diverges with $p_\perp$
- calculate x-section as function of $p_{\perp, min}$

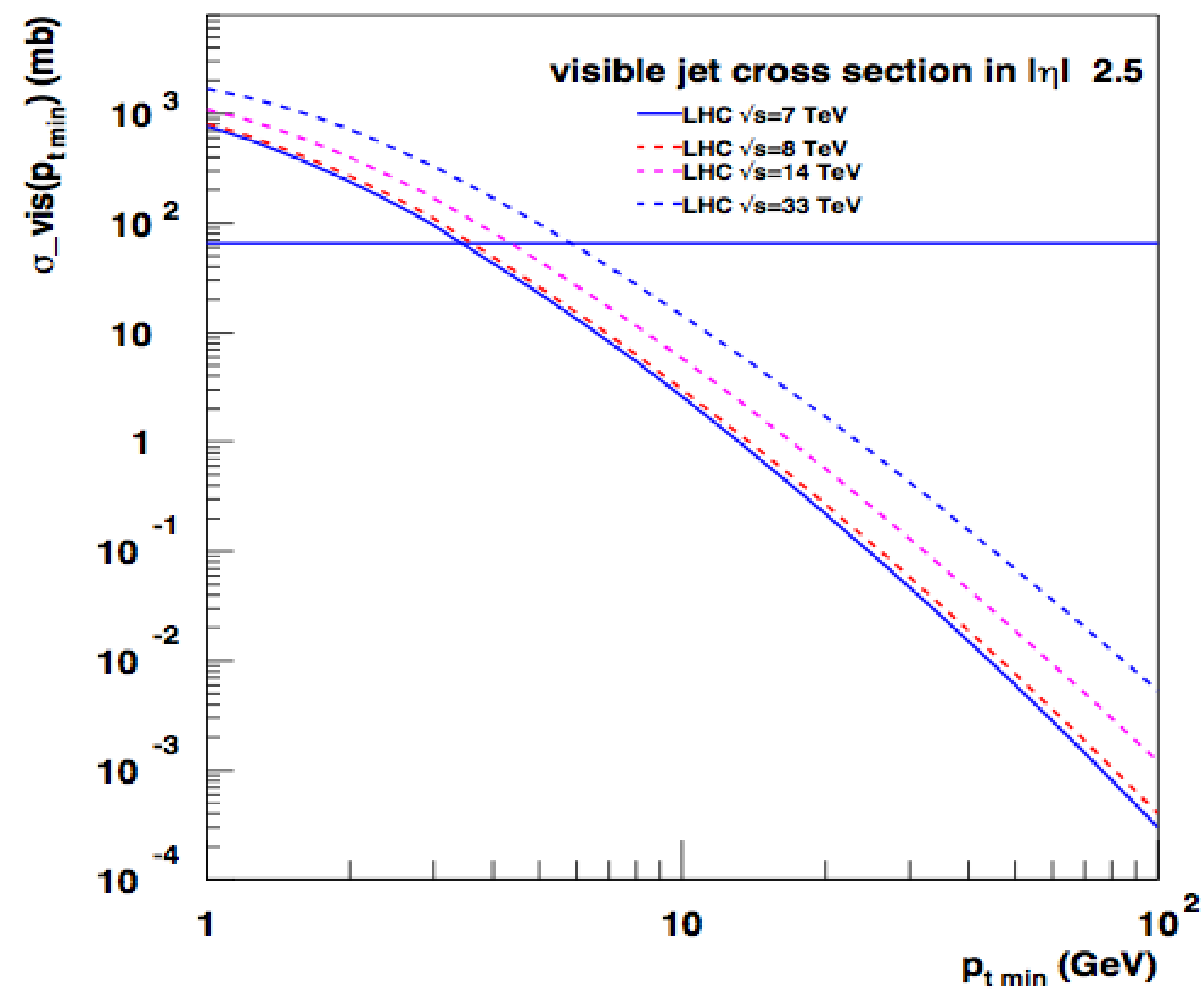
$$\sigma_{\rm hard}(p^2_{\perp\rm min}) = \int_{p^2_{\perp\rm min}} \frac{d\sigma_{\rm hard}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

Partonic Cross sections

- Cross section at LHC

$$\sigma_{\text{hard}}(p^2_{\perp\min}) = \int_{p^2_{\perp\min}} \frac{d\sigma_{\text{hard}}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$





➔ **Partonic x-section exceeds total x-section !!!**

➔ happens even for visible range !

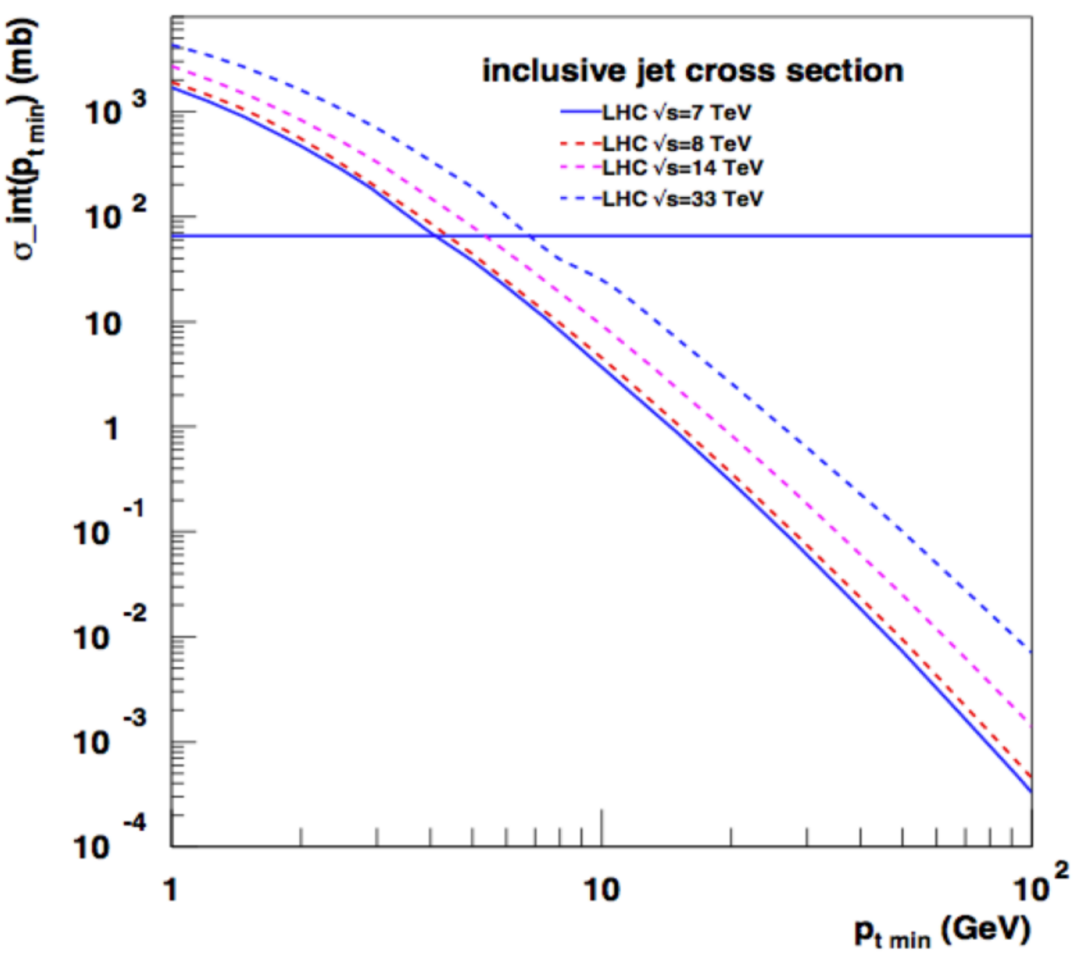
Partonic Cross Section

- Basic partonic perturbative cross section

$$\sigma_{\text{hard}}(p^2_{\perp\text{min}}) = \int_{p^2_{\perp\text{min}}} \frac{d\sigma_{\text{hard}}(p^2_{\perp})}{dp^2_{\perp}} dp^2_{\perp}$$

- diverges faster than $1/p^2{}_{\perp,min}$ as $p_{\perp,min}$ and exceeds eventually total inelastic (non-diffractive) cross section

  - Interaction x-section exceeds total xsection
  - happens well above λ_{QCD}
  - in perturbative region



Multiparton Interaction

- Basic partonic perturbative cross section

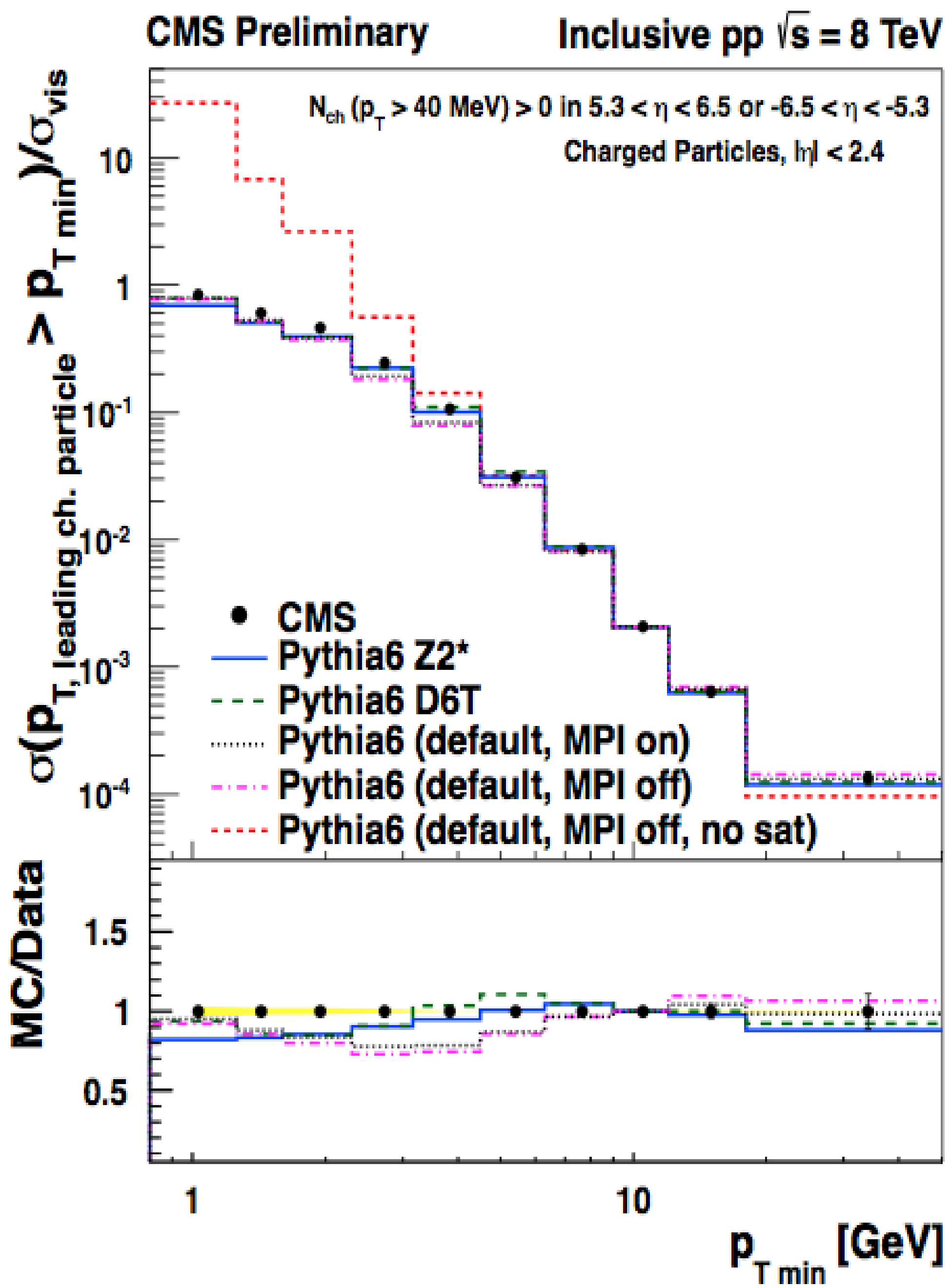
$$\sigma_{\text{hard}}(p^2_{\perp\text{min}}) = \int_{p^2_{\perp\text{min}}} \frac{d\sigma_{\text{hard}}(p^2_{\perp})}{dp^2_{\perp}} dp^2_{\perp}$$

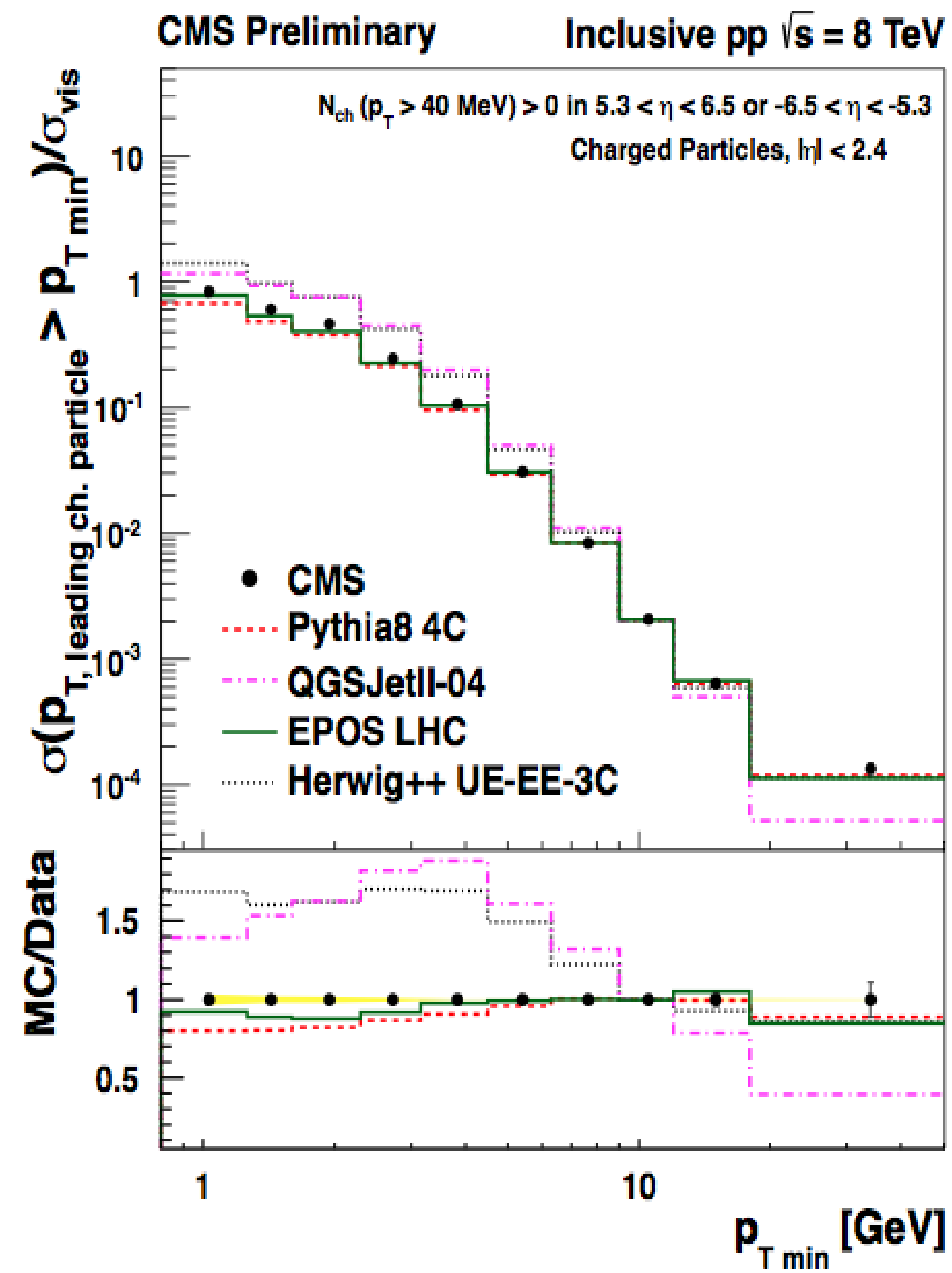
- diverges faster than $1/p^2{}_{\perp,min}$ as $p_{\perp,min}$ and exceeds eventually total inelastic (non-diffractive) cross section

HELP ....

HOW to solve this ?

Comparison with CMS measurement





- Saturation effects are clearly seen !
- What is the reason for this ?

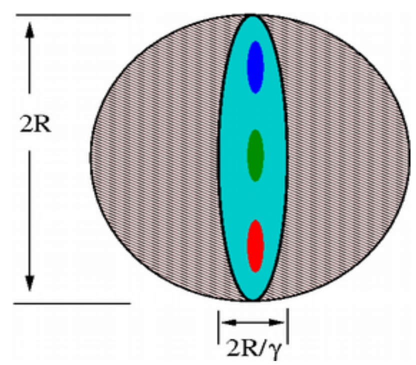
Parton Distribution Functions

- number of gluons in long. phase space dx/x:

$$xg(x,\mu^2)dx/x$$

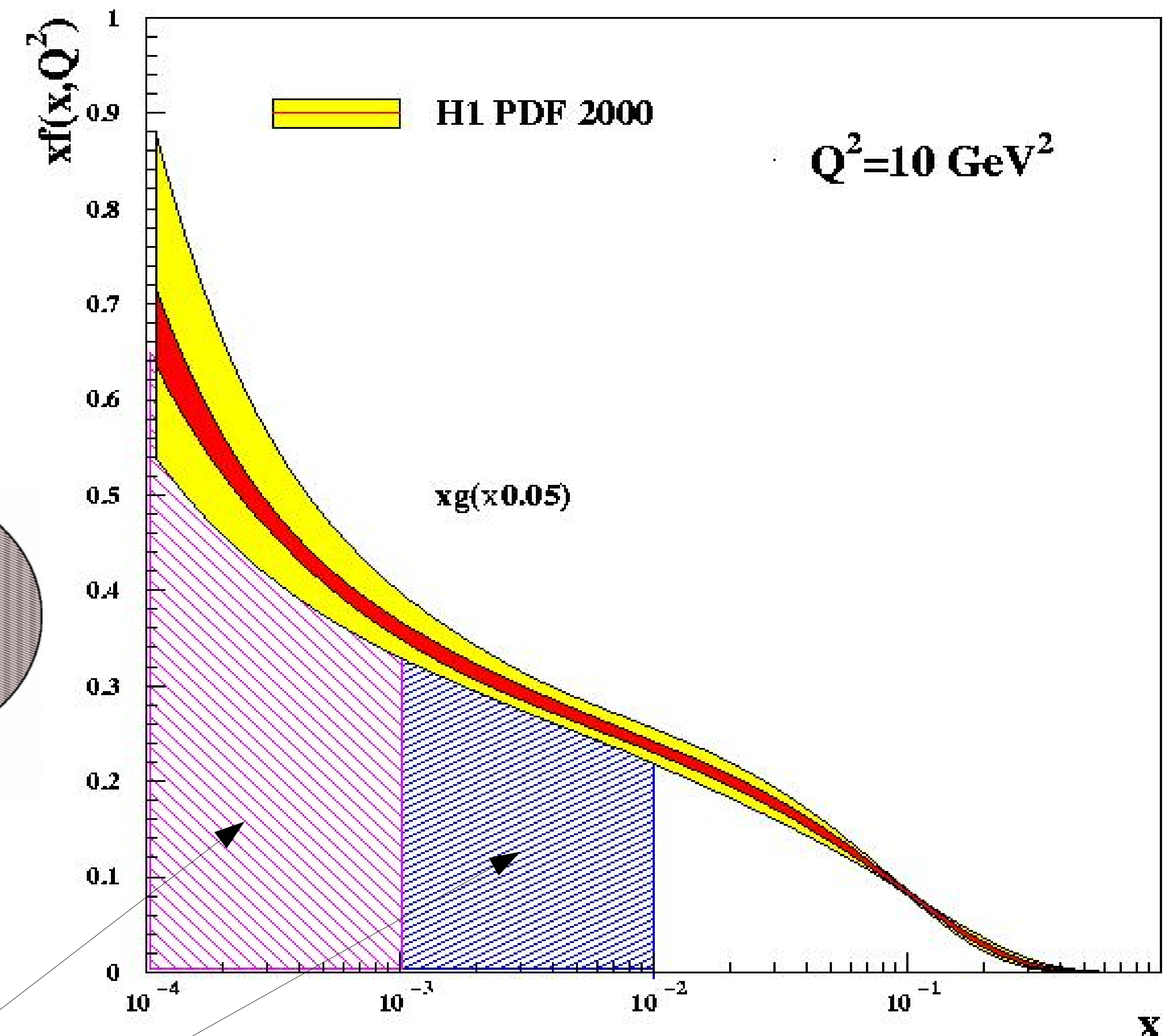
- occupation area: nr of gluons x (trans size)^2

$$g(x,\mu^2)\frac{1}{\mu^2}$$



- saturation starts when:

$$\frac{\alpha_s(\mu^2)}{\mu^2}xg(x,\mu^2)\frac{dx}{x} \geq \pi R^2$$



- gluon density is very large:~ 90 or 45 Gluons !!!!!
- with R ~ 1 GeV^{-1} we obtain:

$$\frac{0.2}{10GeV^2}90 \sim \pi R^2 \quad !!!!!$$

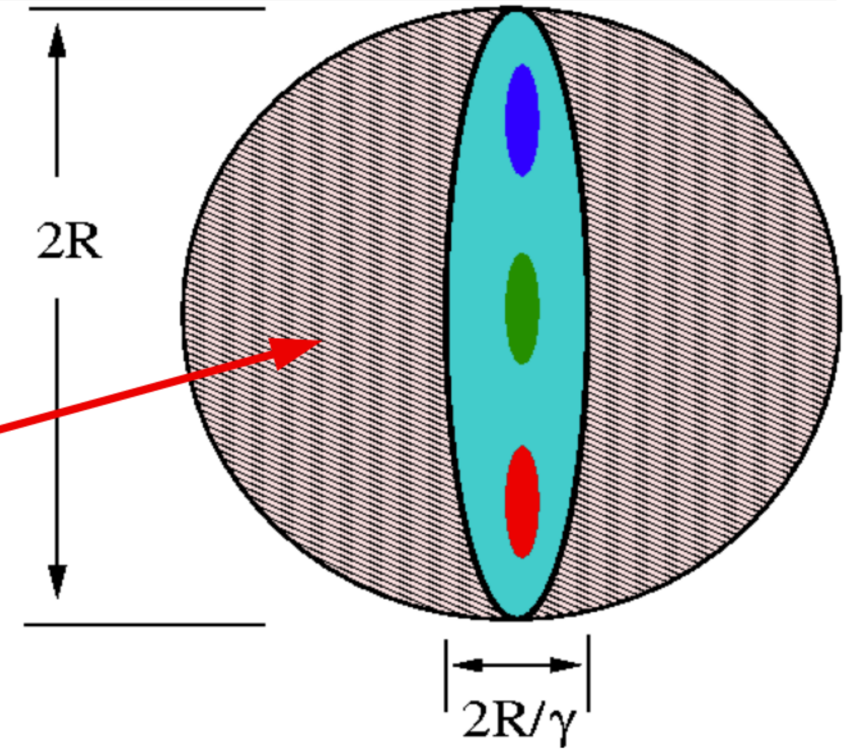
Parton saturation

- number of gluons in long. phase space dx/x :

$$xg(x,\mu^2)dx/x = xg(x,\mu^2)d\log x$$

- occupation area:
  nr of gluons x (trans size)^2

$$g(x,\mu^2)\frac{1}{\mu^2}$$

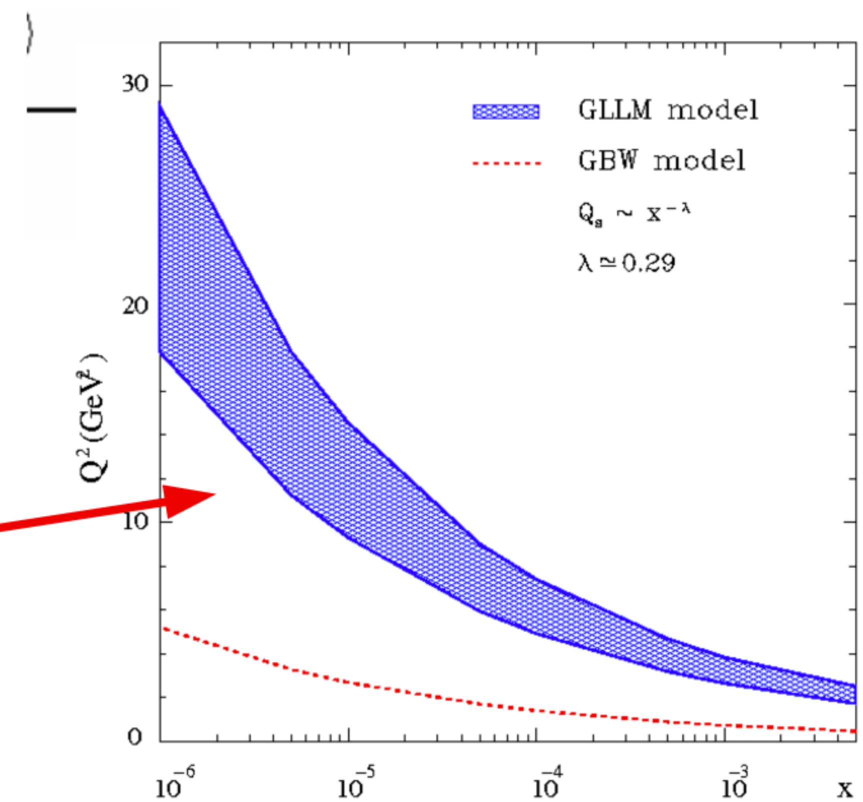


- saturation starts when:

$$\frac{\alpha_s(\mu^2)}{\mu^2}xg(x,\mu^2)\frac{dx}{x} \geq \pi R^2$$

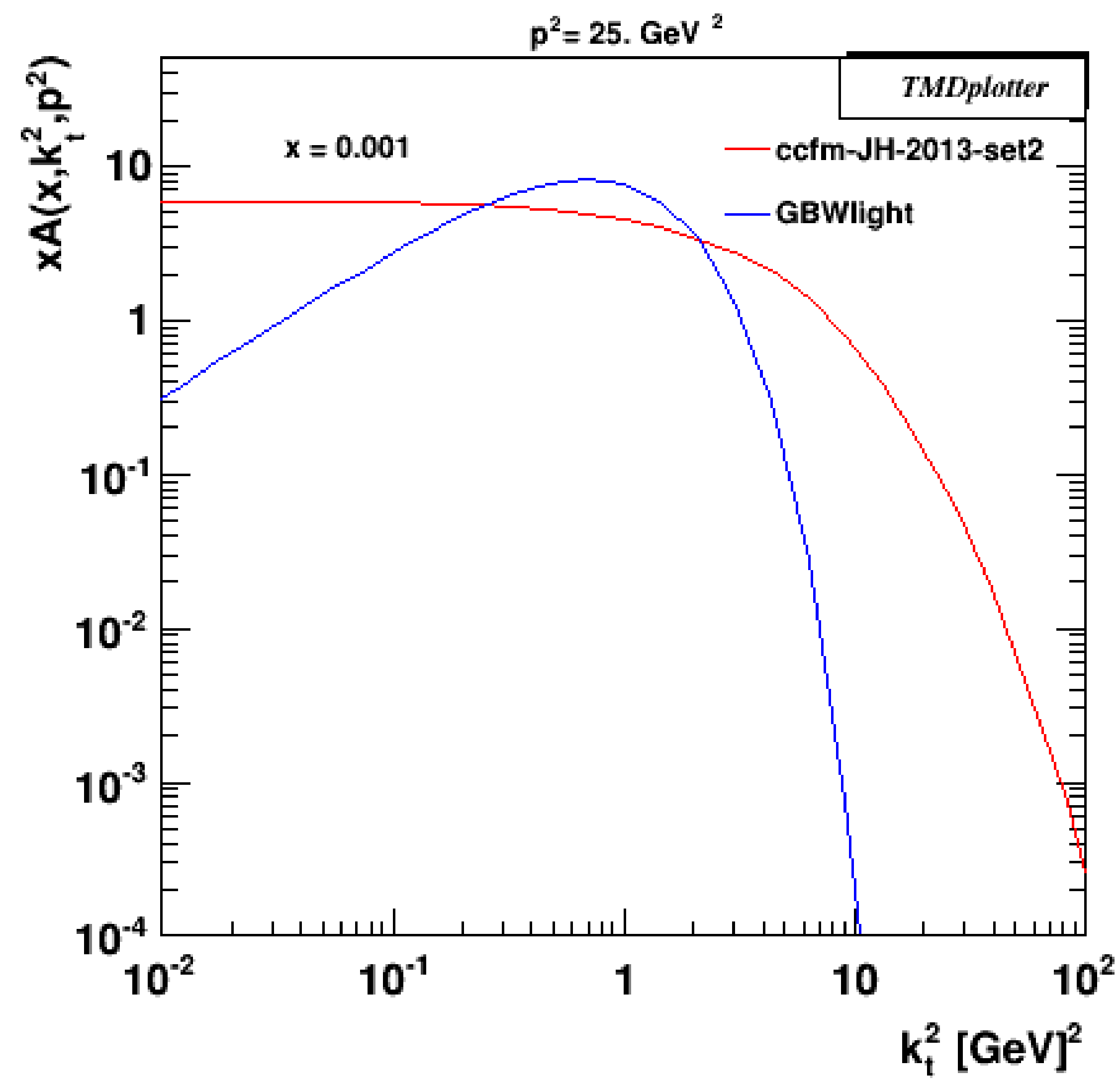
- define saturation scale:

$$Q_s^2(x) \sim \frac{\alpha_s(Q_s^2)g(x,Q_s^2)}{\pi R^2}$$



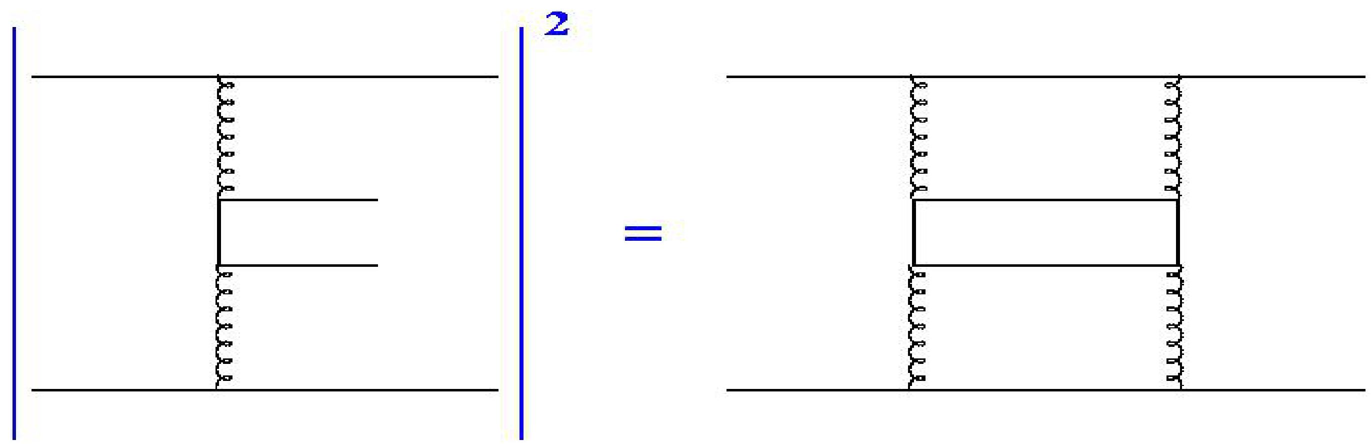
Gluon densities

- recombination best seen as function of k_t
- density is largest at small $k_t \rightarrow$ largest suppression
    - density vanishes at small k_t

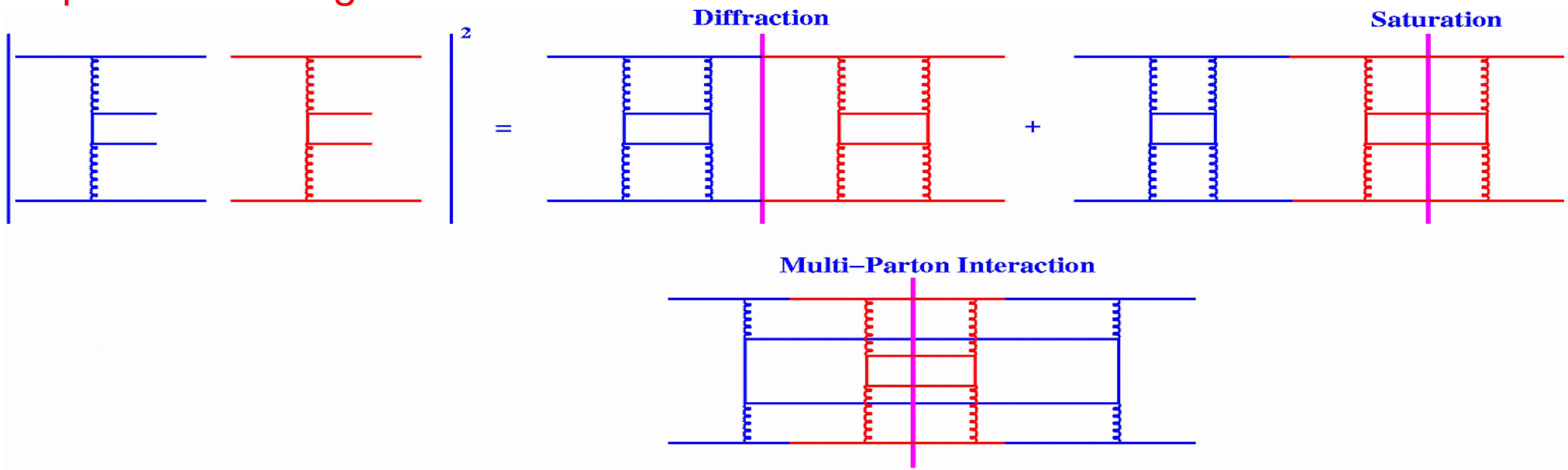


Toy Model for highest energies

- relation of diffraction – multiple scatterings – saturation
  (AGK Abramovsky-Gribov-Kancheli ...)
- single parton exchange:



- 2-parton exchange:

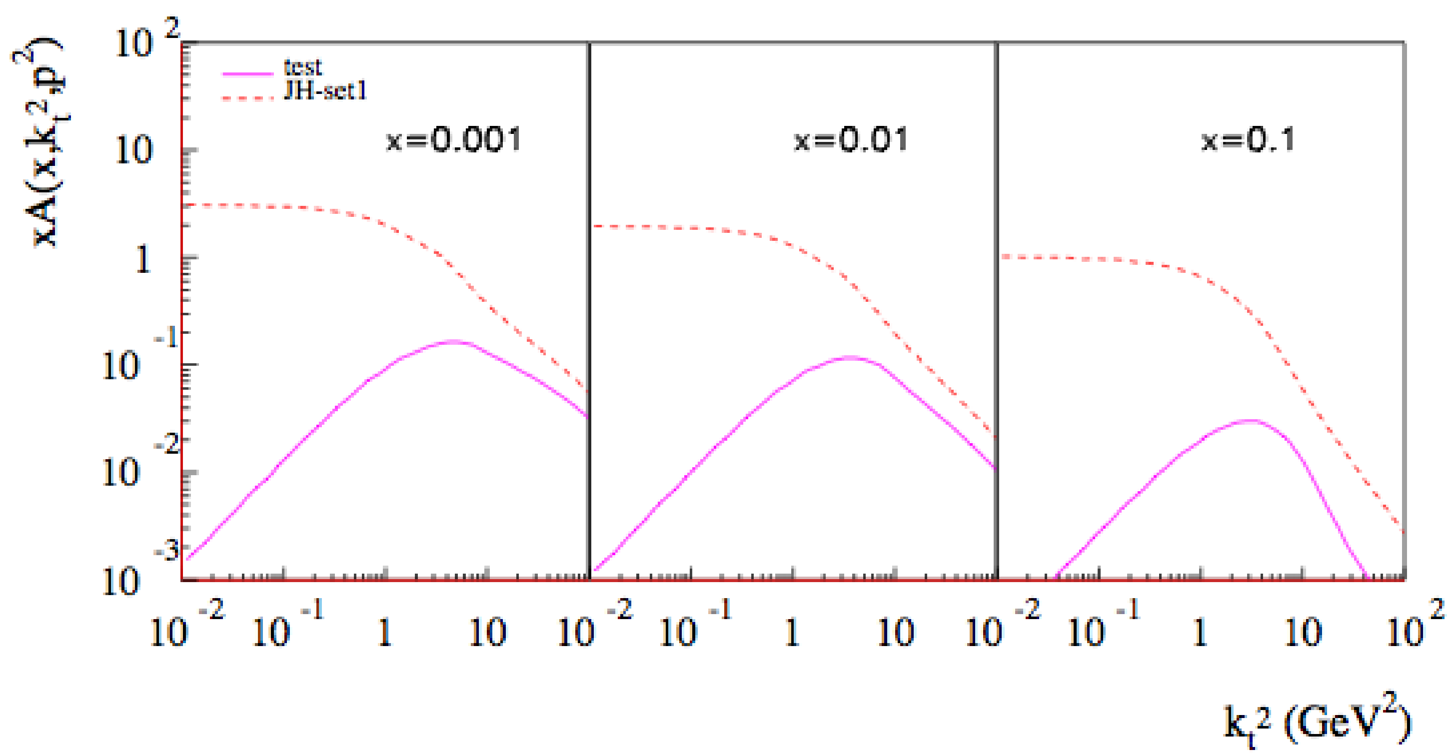


Small p_t behavior of x-section

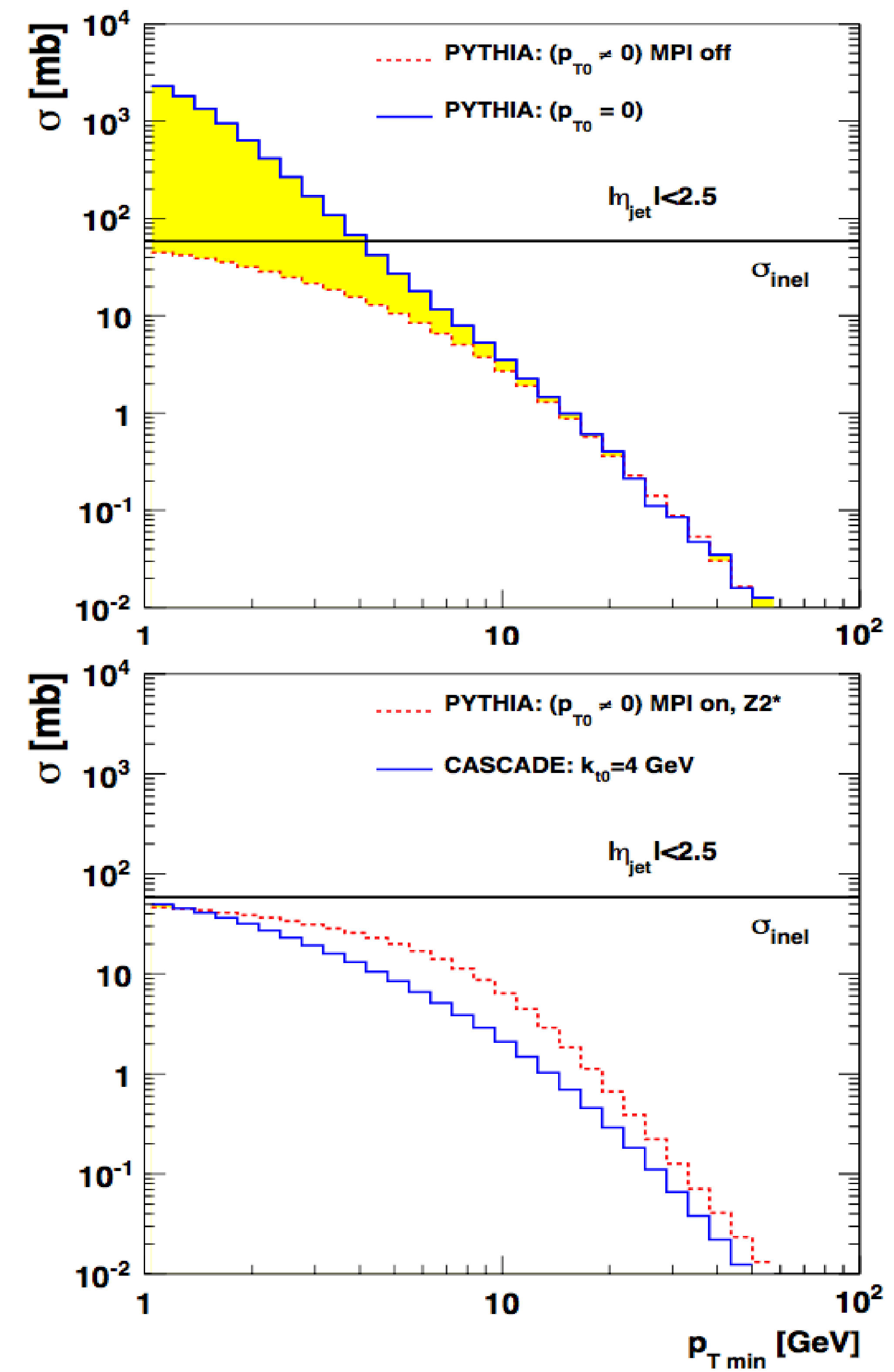
- $\sigma(p_t) \sim \alpha_s(p_T{}^2)/p_T{}^4$
- simple ansatz for taming:

$$\frac{\alpha_s^2(p_{T0}^2 + p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}$$

- or change kt dependence of uPDF at small kt



A. Grebenyuk, F. Hautmann, H. Jung, P. Katsas, and A. Knutsson. Jet production and the inelastic pp cross section at the LHC. Phys.Rev., D86:117501, 2012.



Multiparton Interaction

- Basic partonic perturbative cross section

$$\sigma_{\text{hard}}(p^2_{\perp\min}) = \int_{p^2_{\perp\min}} \frac{d\sigma_{\text{hard}}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

- diverges faster than $1/p^2_{\perp,\min}$ as $p_{\perp,\min}$ and exceeds eventually total inelastic (non-diffractive) cross section eventually total inelastic (non-diffractive) cross section, resulting in more than 1 interaction per event (multiple interactions, MI).

- Average number of interactions per event is given by:

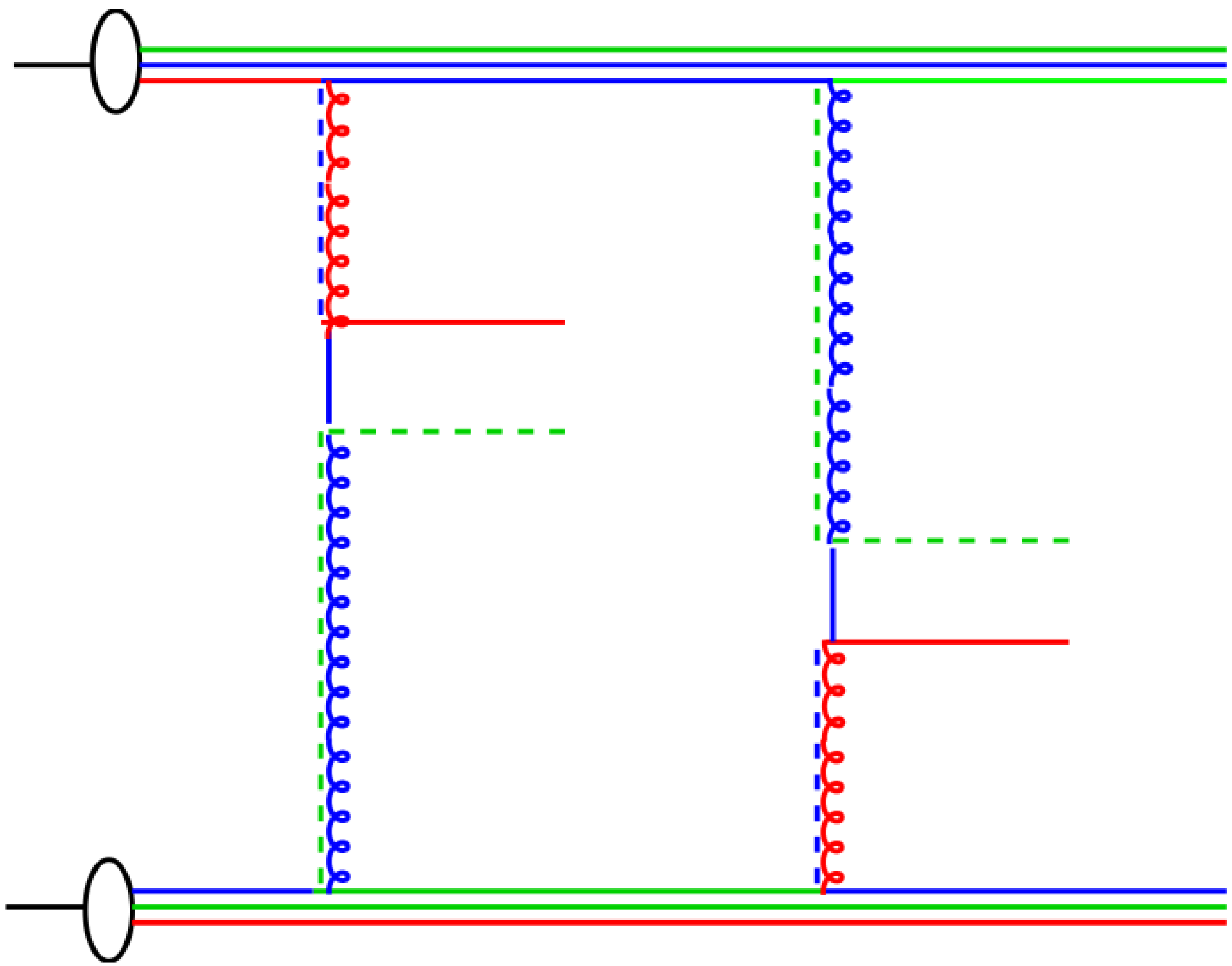
$$\langle n \rangle = \frac{\sigma_{\text{hard}}(p_{\perp\min})}{\sigma_{nd}}$$

- It depends on how soft interactions are treated, ***BUT*** also on the parton densities and factorization scheme, parton evolution (DGLAP/BFKL) !!!!!!!!

Models for Multi-Parton Interaction

- The very simple model
  - ➔ add secondary interactions
  - ➔ first model by: T. Sjostrand, M. Zijl PRD 36 (1987) 2019
- order scatterings in p_t
  - ➔ use of sudakov form factor
  - ➔ result in Poisson distribution of number of scatterings:

with $$p_r = \frac{\mu^r}{r!} \exp\left(-\mu\right)$$



$$\mu = \langle n \rangle = \frac{1}{\sigma_{nd}} \int_{p_{\perp\text{min}}}^{p_{\perp\text{max}}} \frac{d\sigma_{\text{hard}}}{dp'_\perp} dp'_\perp$$

Formalism for MI (Sjostrand, Zijl) I

T. Sjostrand, M. Zijl PRD 36 (1987) 2019

- define:

$$p(x_t) = \frac{1}{\sigma_{nd}} \frac{d\sigma}{dx_t}$$

- probability for hardest scattering at x_{t1}:

$$P_1 = p(x_{t1}) \exp\left(-\int_{x_{t1}}^{1} p(x')dx'\right)$$

- probability for second hardest scattering at x_{t2}:

$$P_2 = \int_{x_{t2}}^{1} dx_{t1} p(x_{t1}) \exp\left(-\int_{x_{t1}}^{1} p(x')dx'\right) p(x_{t2}) \exp\left(-\int_{x_{t2}}^{x_{t1}} p(x')dx'\right)$$

- probability for 3rd hardest scattering at x_{t3}:

$$\begin{aligned} P_3 \quad = \quad & \int_{x_{t2}}^{1} dx_{t1} \int_{x_{t3}}^{x_{t1}} dx_{t2} p(x_{t1}) \exp\left(-\int_{x_{t1}}^{1} p(x')dx'\right) \\ & \times \; p(x_{t2}) \exp\left(-\int_{x_{t2}}^{x_{t1}} p(x')dx'\right) p(x_{t3}) \exp\left(-\int_{x_{t3}}^{x_{t2}} p(x')dx'\right) \end{aligned}$$

- for nth scattering:

$$P_N = p(x_{tN}) \frac{1}{(N-1)!} \left(\int_{x_{tN}}^{1} p(x')dx'\right)^{N-1} \exp\left(-\int_{x_{tN}}^{1} p(x')dx'\right)$$

Formalism for MI (Sjostrand, Zijl) II

T. Sjostrand, M. Zijl PRD 36 (1987) 2019

- compare to Poisson distribution:

$$p_r = \frac{\mu^r}{r!} \exp\left(-\mu\right)$$

- total probability to have any scattering at x_{t1}:

$$\begin{aligned} \sum_N P_N &= \sum_N p(x_t) \frac{1}{(N-1)!} \left(\int_{x_t}^1 p(x')dx' \right)^{N-1} \exp\left(- \int_{x_t}^1 p(x')dx' \right) \\ &= p(x_t) \end{aligned}$$

$$\mu = \int_{x_t}^1 p(x')dx' = \frac{1}{\sigma_{nd}} \int_{x_t}^1 \frac{d\sigma}{dx'_t} dx'_t$$

- preserving total probability
- recovering parton model result
  - Poisson distribution with mean
- recover AGK rules...

Factorization

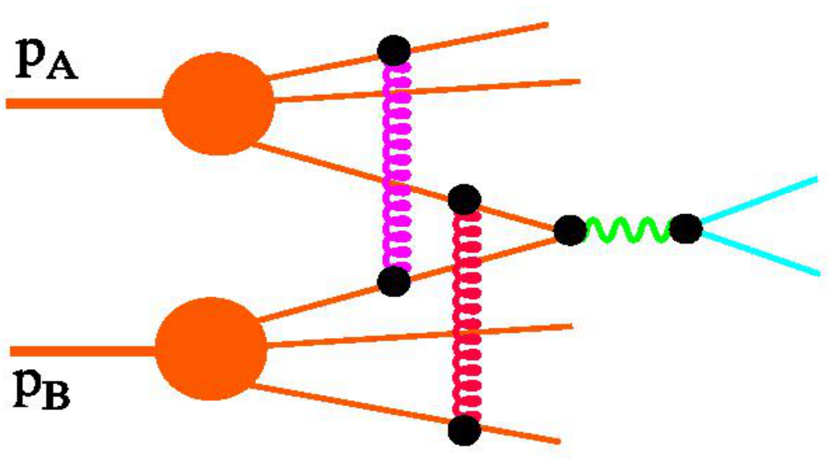
- factorization means:

$$\frac{d\sigma}{dy} = \sum_{a,b} \int_{x_A}^{1} d\xi_A \int_{x_B}^{1} d\xi_B f_A^a(\xi_A,\mu) f_B^b(\xi_B,\mu) \frac{d\hat{\sigma}_{ab}(\mu)}{dy} + \mathcal{O}\left(\left(\frac{m}{P}\right)^p\right)$$

- MPI approach reproduces inclusive jet x-section with

$$\langle n \rangle = \frac{\sigma_{\mathrm{hard}}(p_{\perp\mathrm{min}})}{\sigma_{nd}}$$

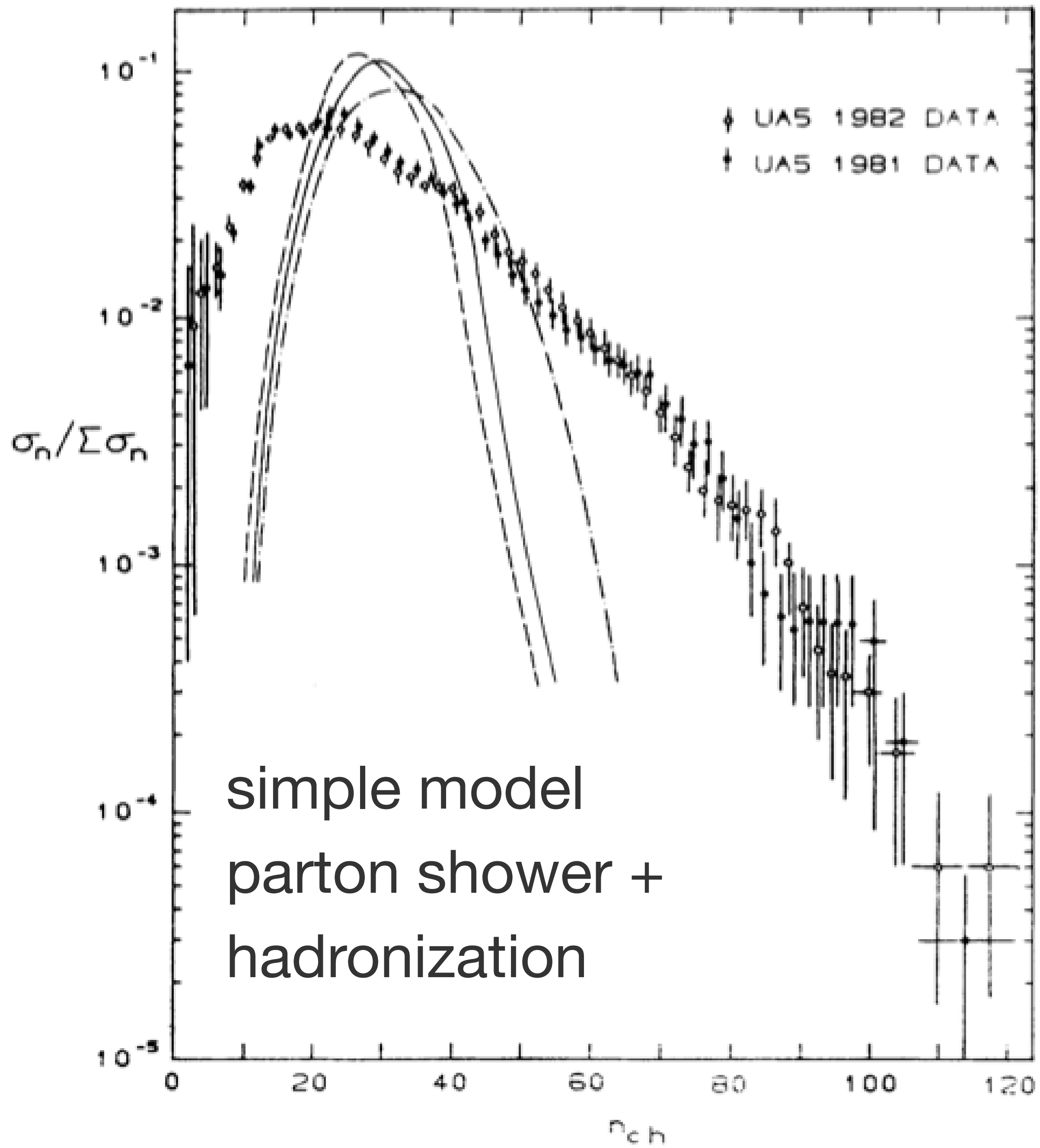
- Similar in Drell-Yan with initial state interactions...
- factorization here does not hold graph-by-graph but only for all ....

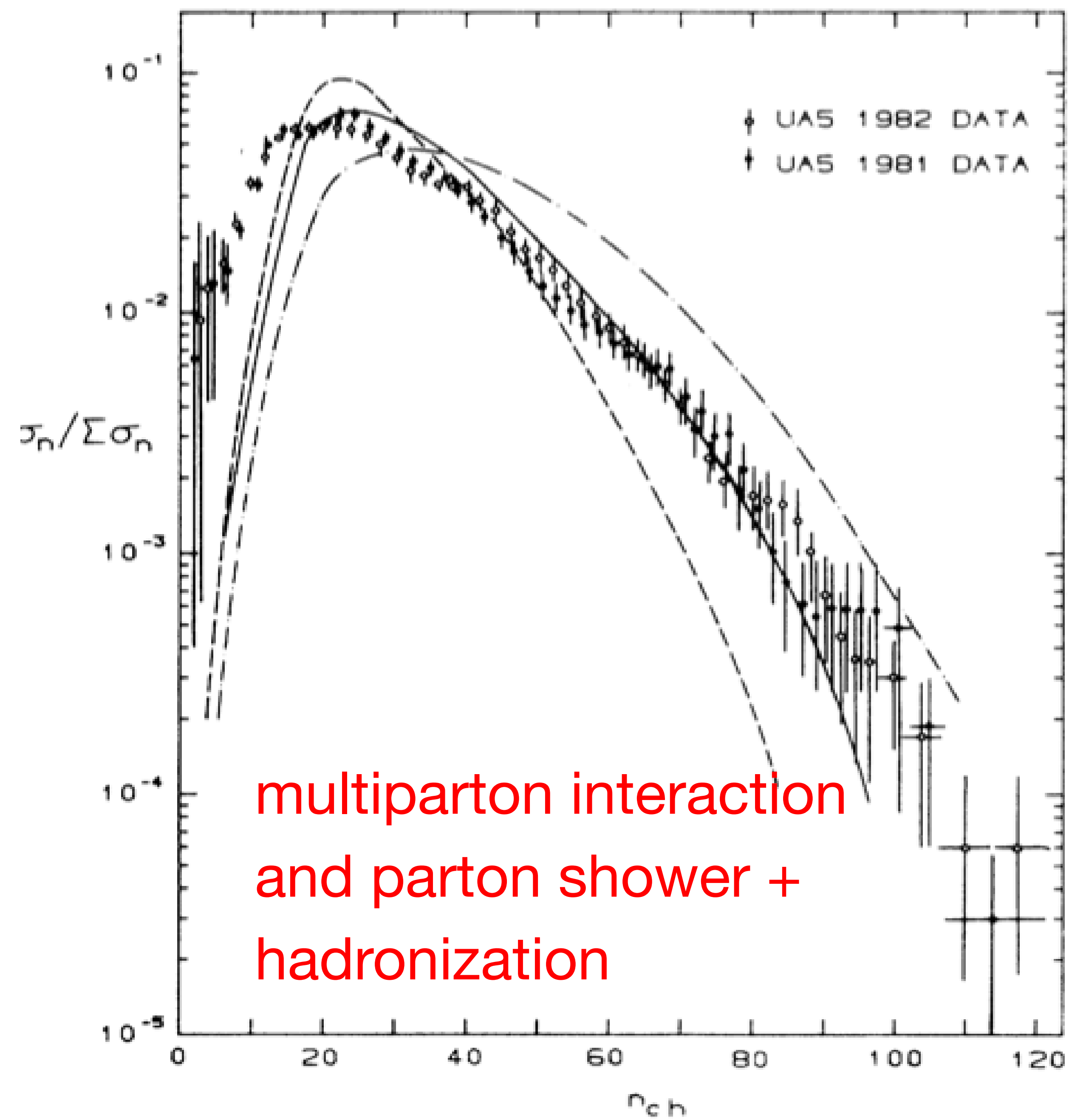


Once upon a time …

- UA5 measurement of charged particle multiplicities (~1982)

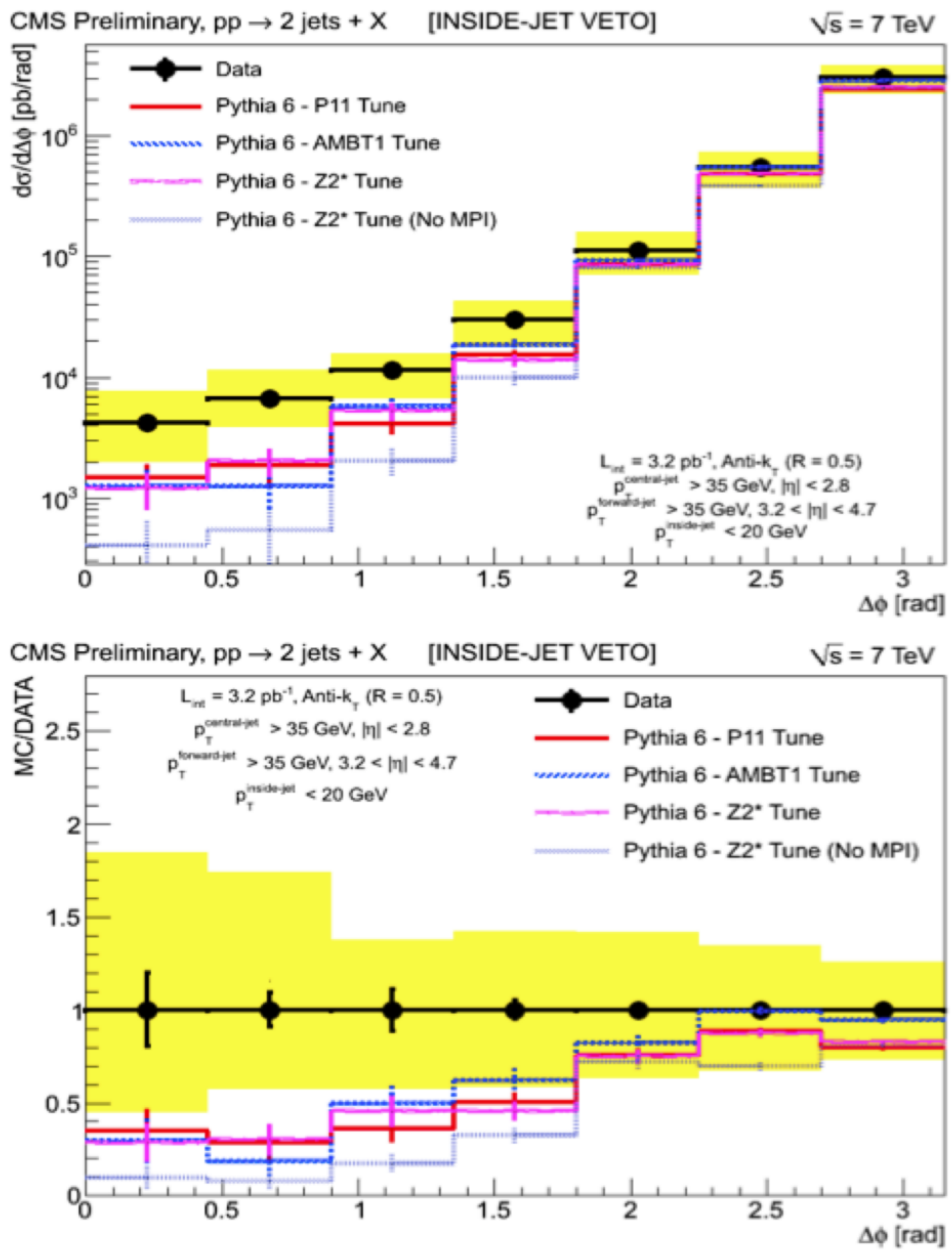
T. Sjostrand, M. Zijl
PRD 36 (1987) 2019

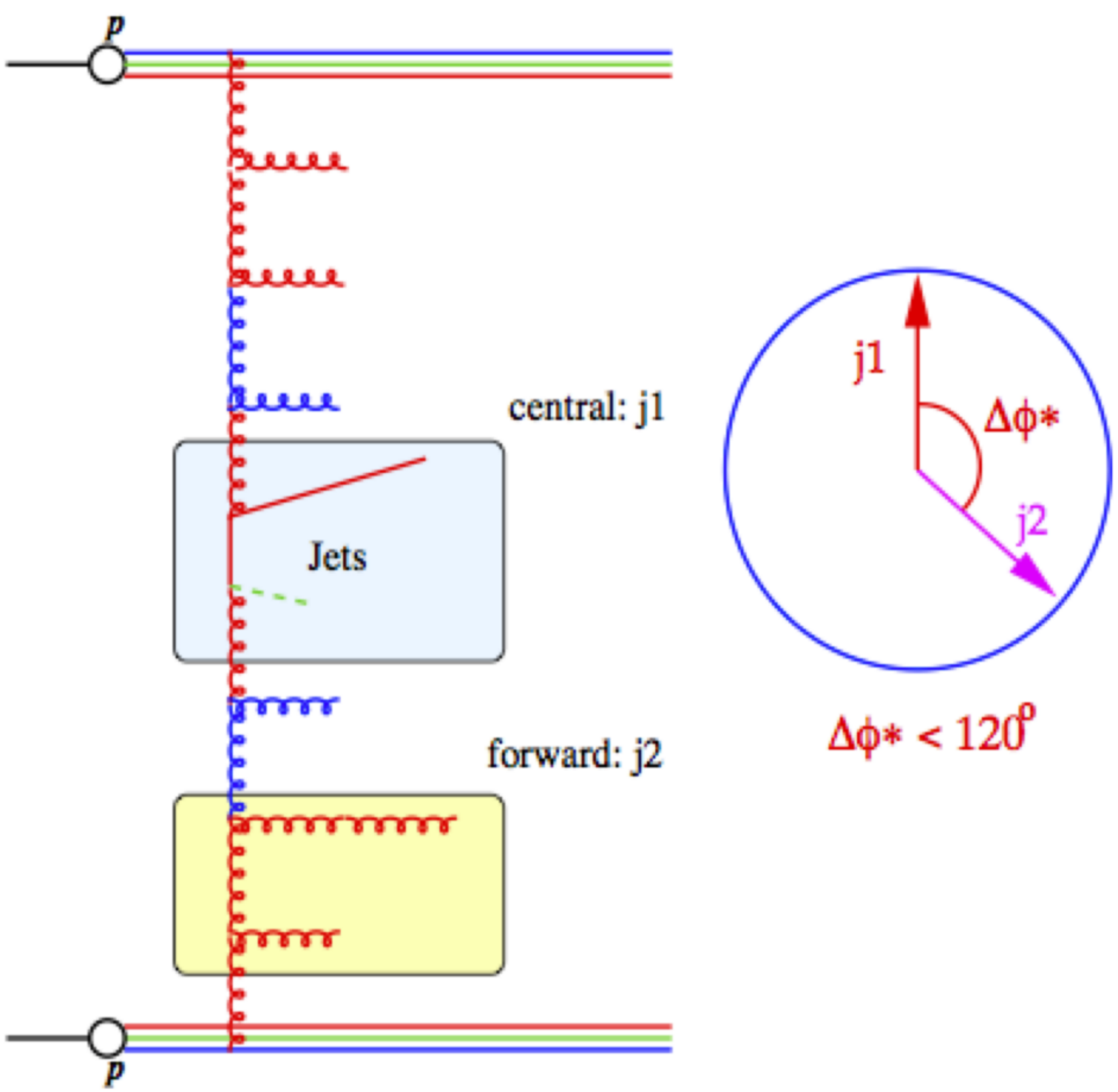




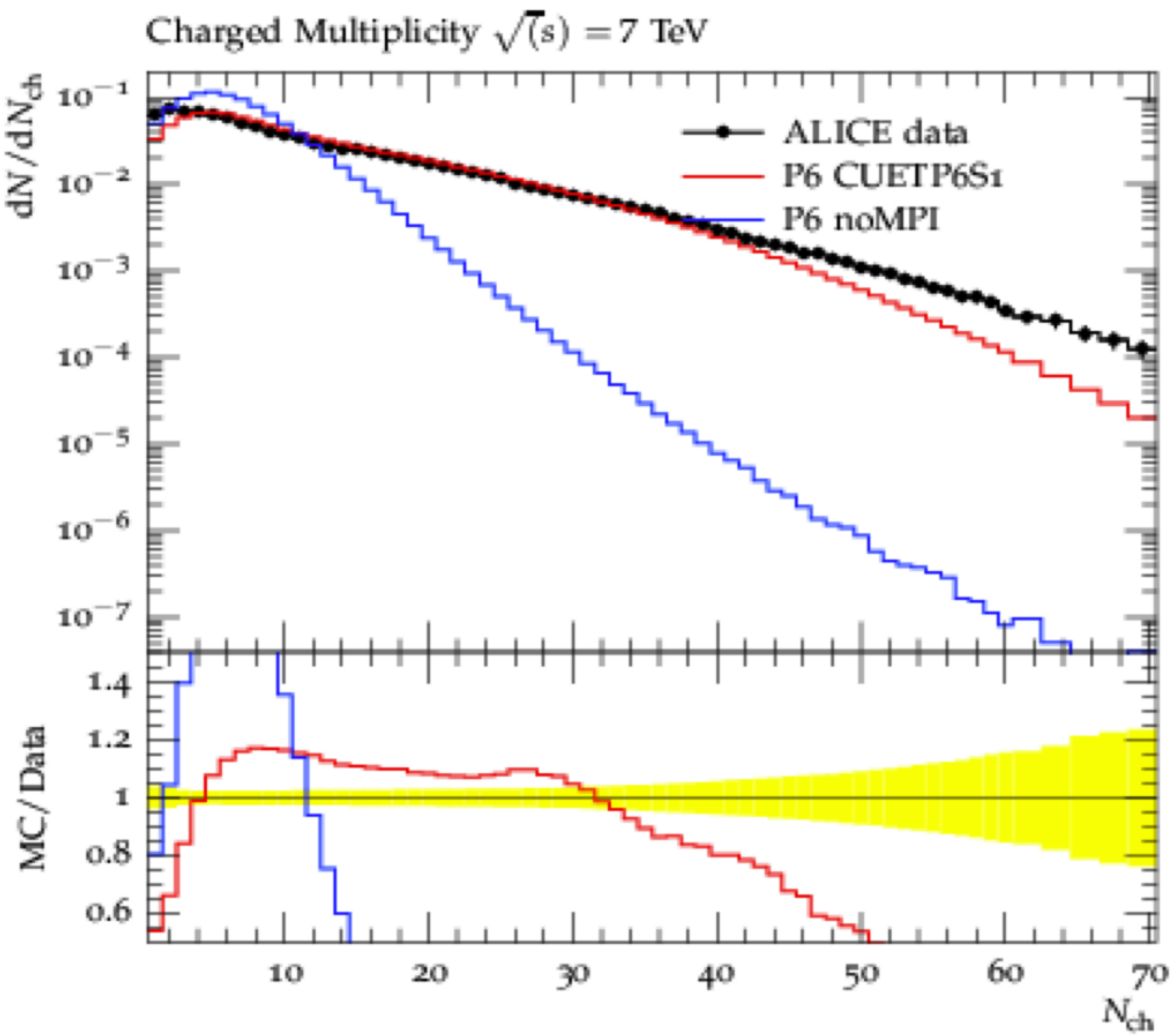
➔ Multiparton interaction help to describe particle multiplicities in minimum bias events ....

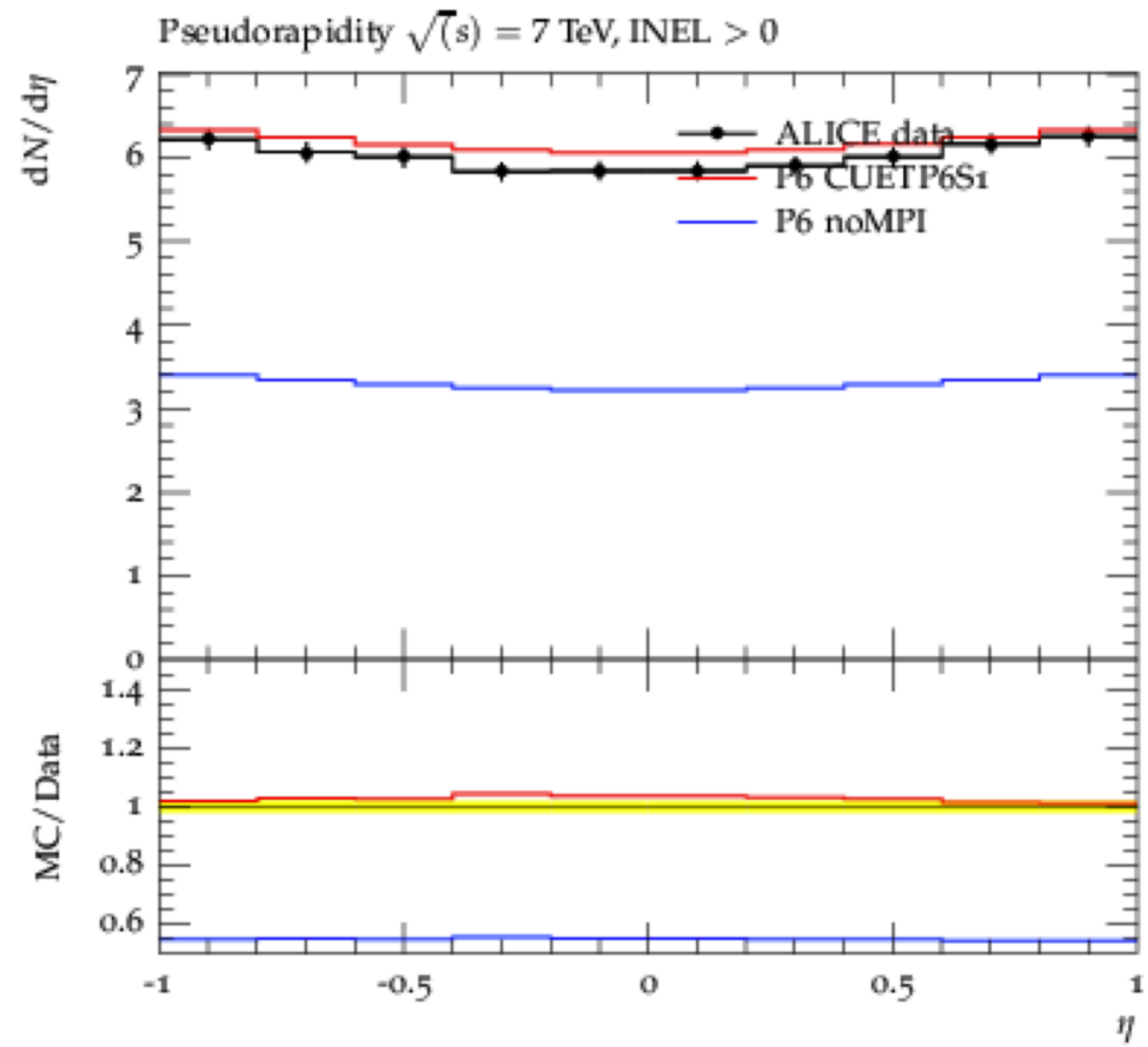
But, there are also other challenges!





Particle spectra at LHC

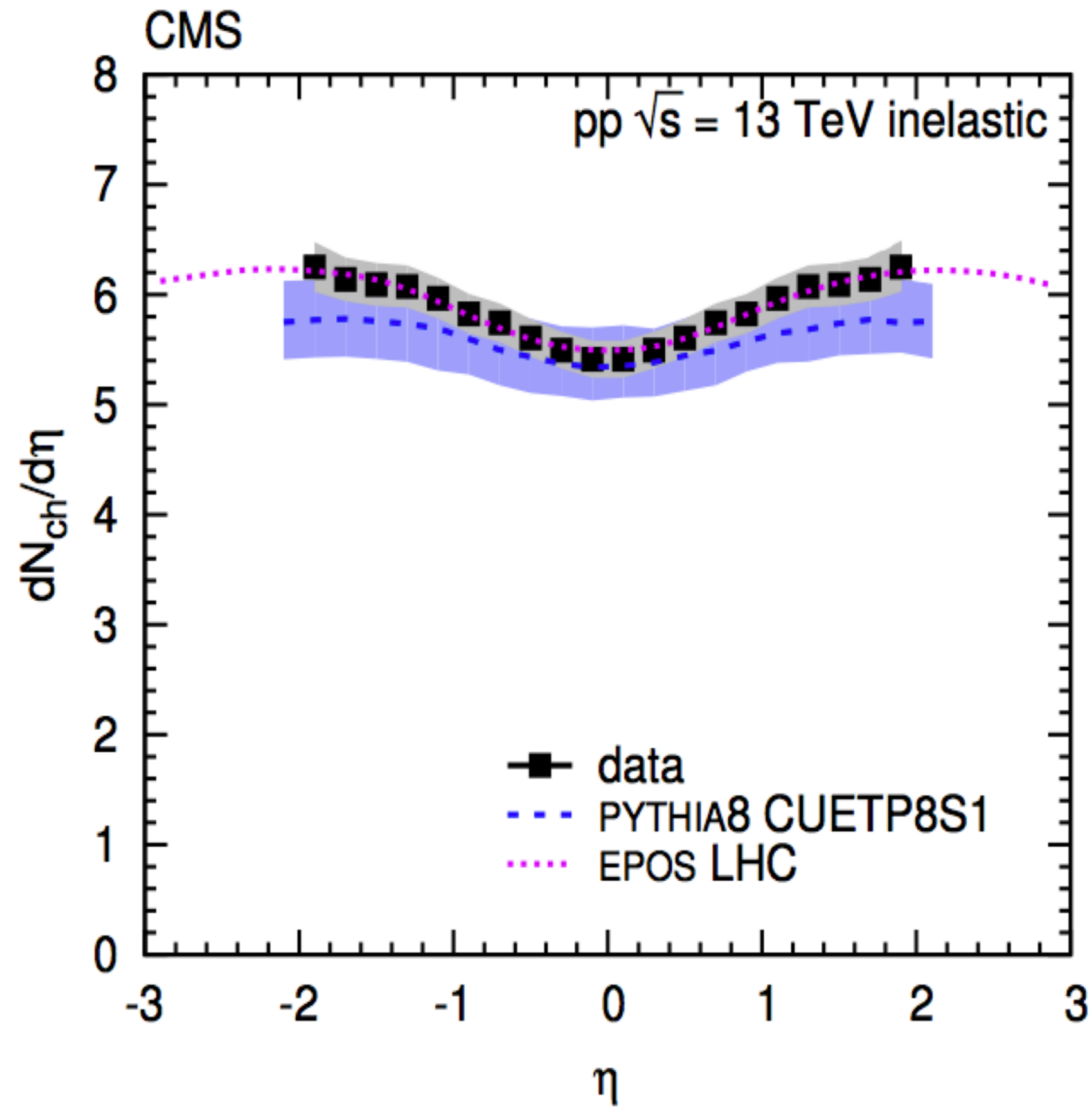




- It's not at all trivial to describe particle multiplicities
- MPI is needed, but even then the spectra are not perfectly described !
- Place for further Tuning !!!

and at 13 TeV

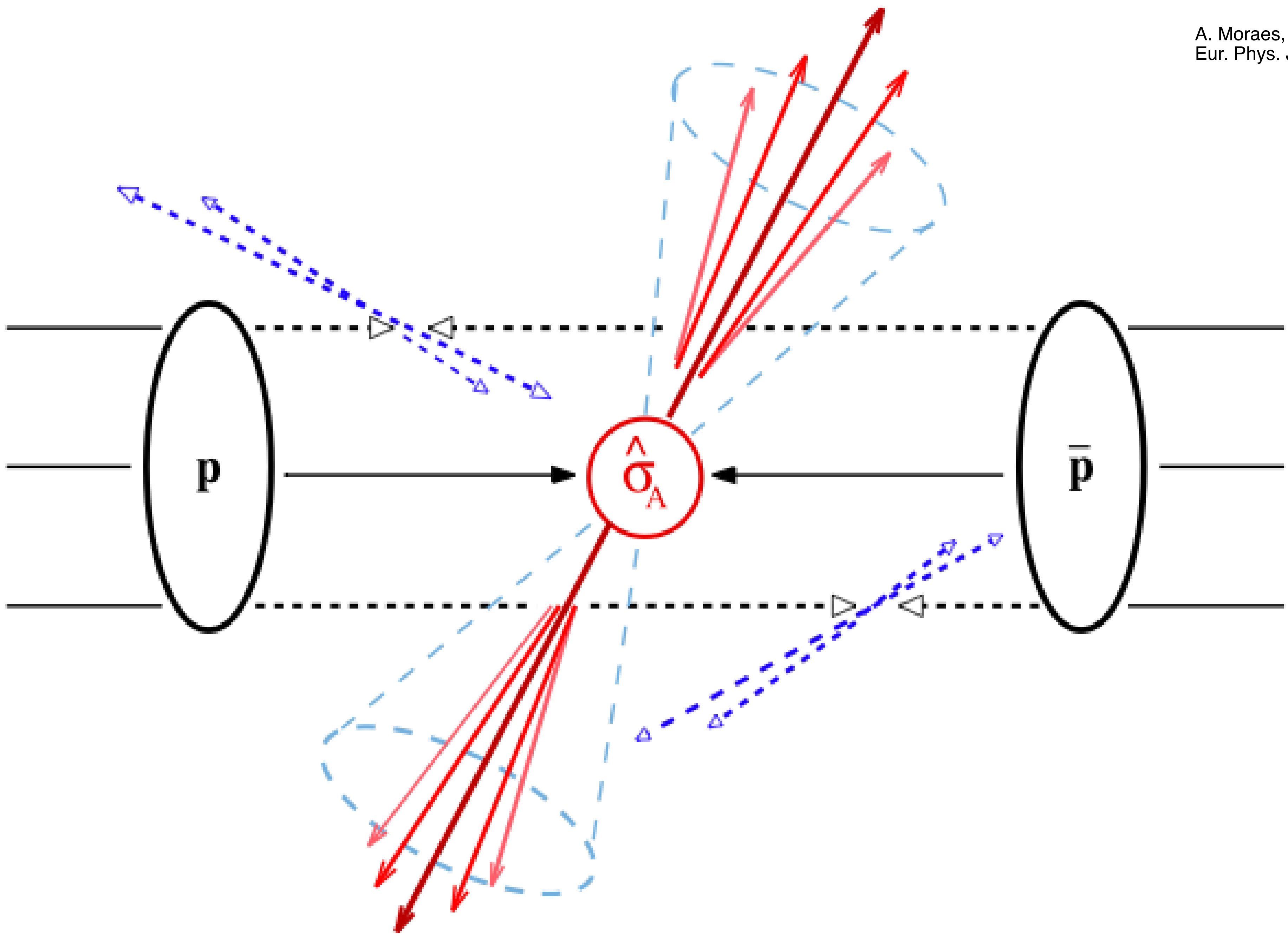
- one of the very first results from LHC at $\sqrt{s} = 13\,TeV$



Evidence for Multi Parton Interaction

- Study of the underlying event structure:
- trigger on high p_t jets, observe additional hadron activity in the transverse regions

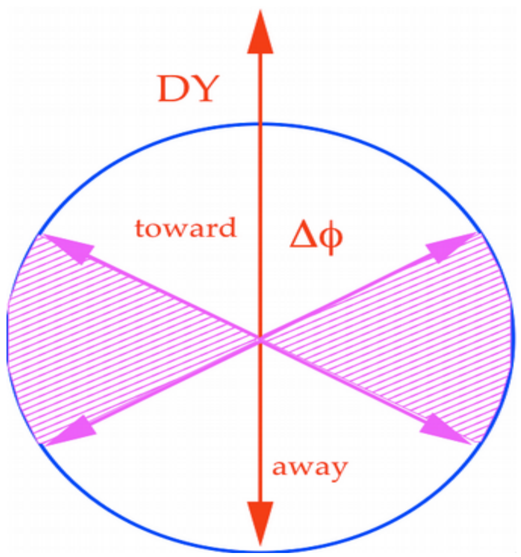
A. Moraes, C. Buttar, and I. Dawson.
Eur. Phys. J., C50:435–466, 2007.

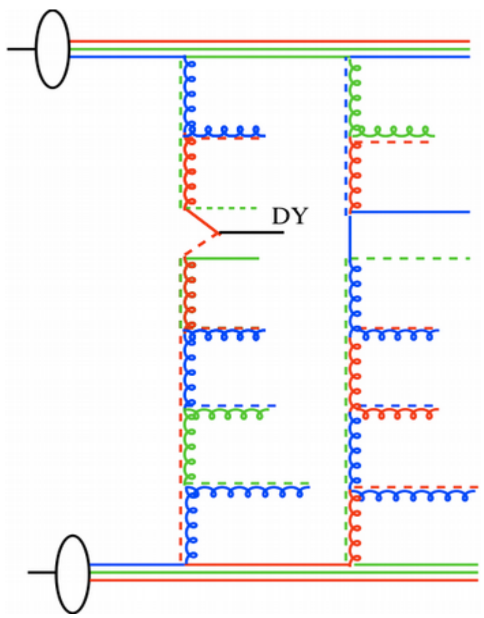


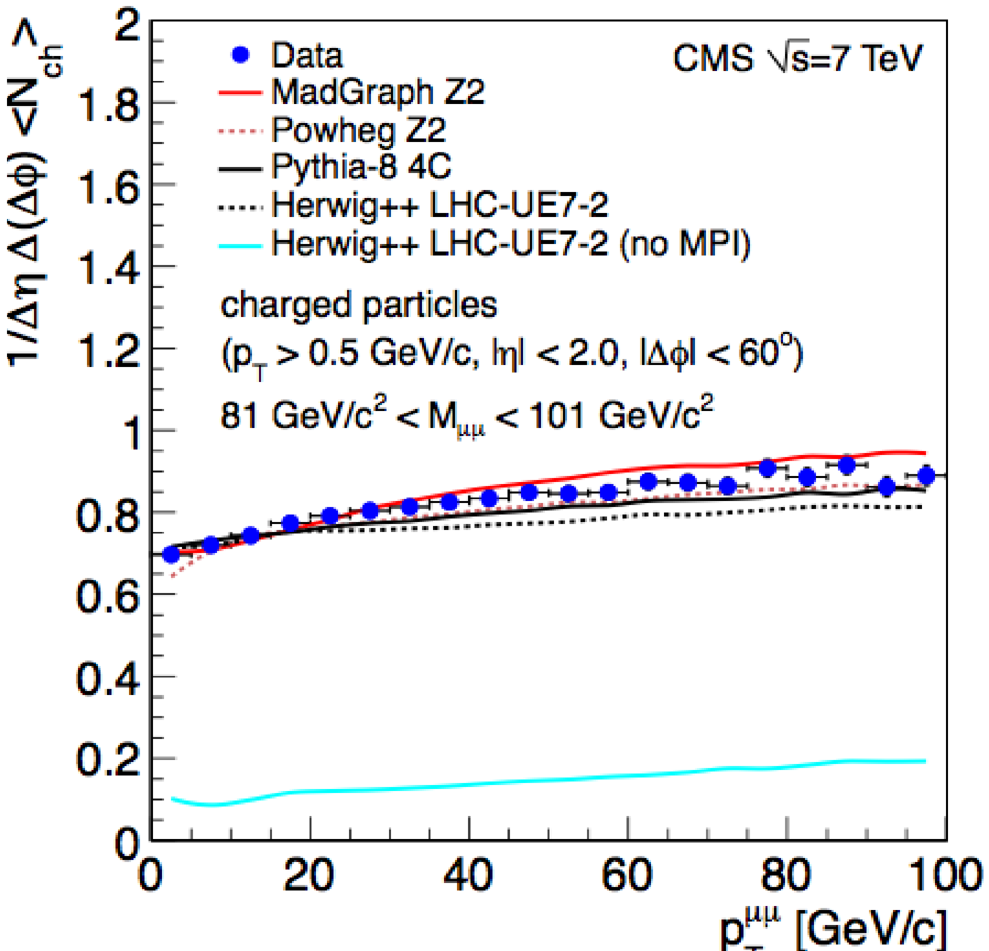
Underlying event study in DY

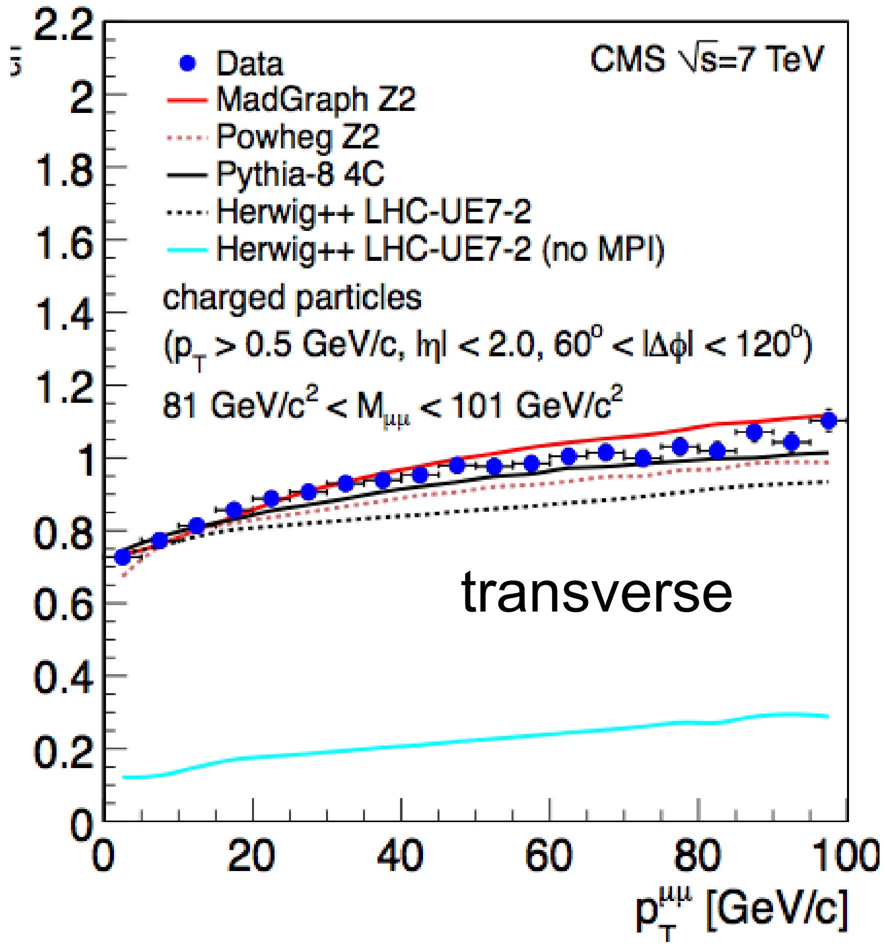
- DY is a clean probe for studying UE
- define toward, away and transverse regions
    - toward region has least contribution from hard process (except the decay leptons)

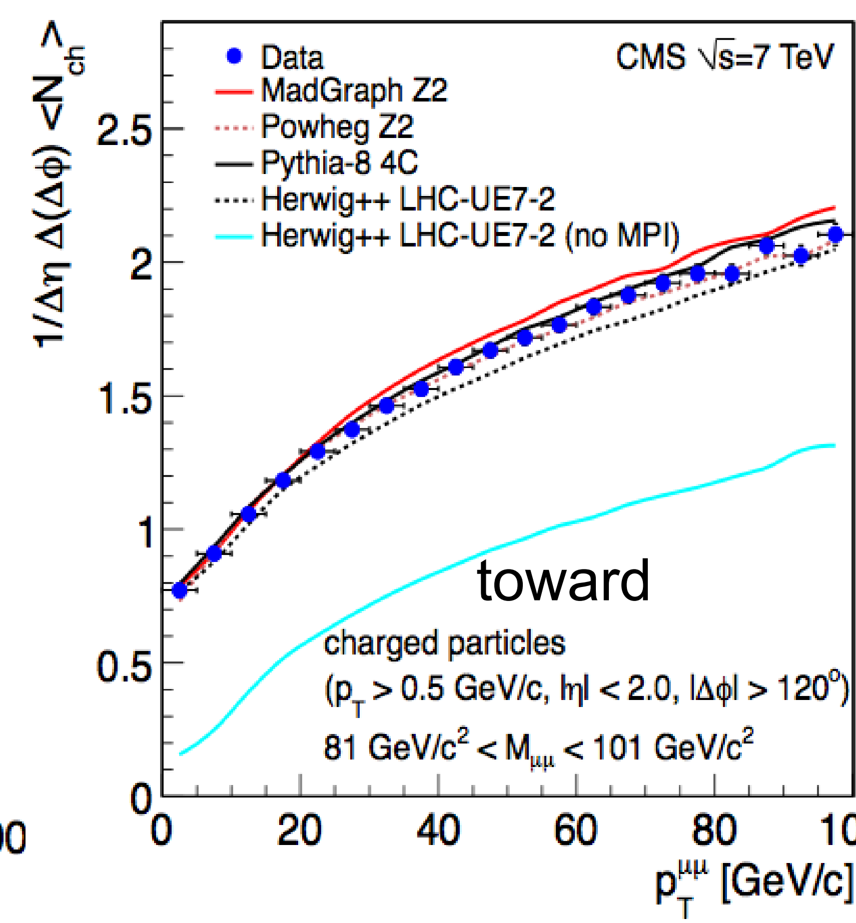
QCD-11-012



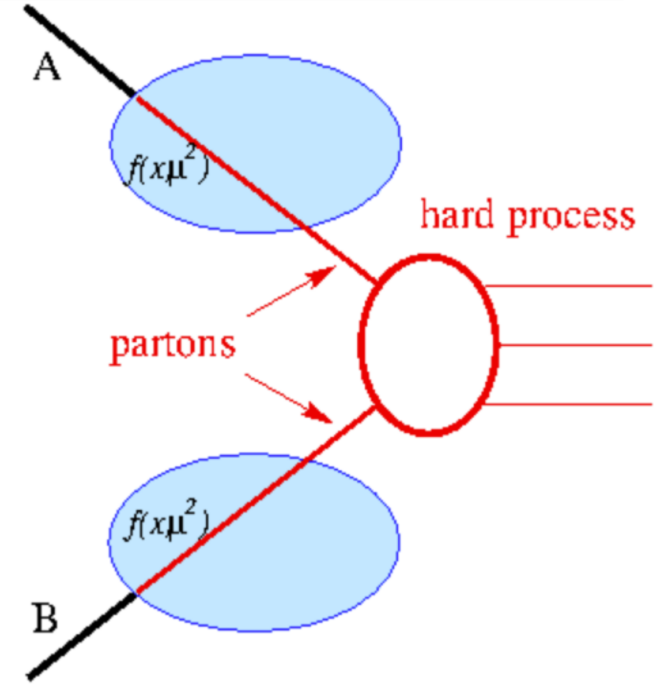








Adding back what was neglected before ...



- The standard ansatz: collinear factorization

$$\sigma = f_i^A(x_1,\mu^2)\hat{\sigma}(i+j\to X)f_j^B(x_2,\mu^2)$$

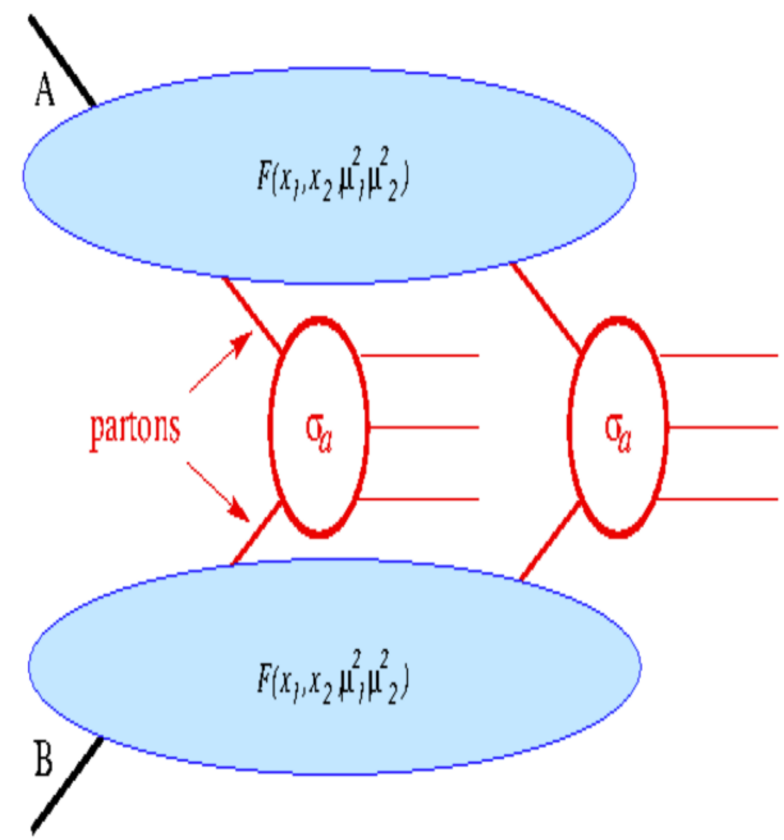
or in detail:

$$\frac{d\sigma}{dy} = \sum_{a,b}\int_{x_A}^1 d\xi_A \int_{x_B}^1 d\xi_B f_A^a(\xi_A,\mu) f_B^b(\xi_B,\mu)\frac{d\hat{\sigma}_{ab}(\mu)}{dy} + \mathcal{O}\left(\left(\frac{m}{\mu}\right)^n\right)$$

- terms which are suppressed by powers 1/[1] are not covered by factorization theorem.
- The limitations:

$$\sigma = c_1 f_g f_g + c_2 f_q f_q + c_3 f_g F + c_4 F F$$

  - last terms are suppressed by powers of [1]
  - leading to double parton scattering



Some power suppressed terms ….

- In parton evolution with k_t dependent splitting functions we have some of the power suppressed terms:

$$\mathcal{P}_{gq}(z, q_t, k_t) = P_{qg,DGLAP}(z)\left(1 + \sum_{n=0}^{\infty} b_n(z)(k_t^2/q_t^2)^n\right)$$

- Can at least hard perturbative contributions simulated by a more advanced parton evolution ?

  - yes …... to some extend....

Double-Parton Interactions at LHC

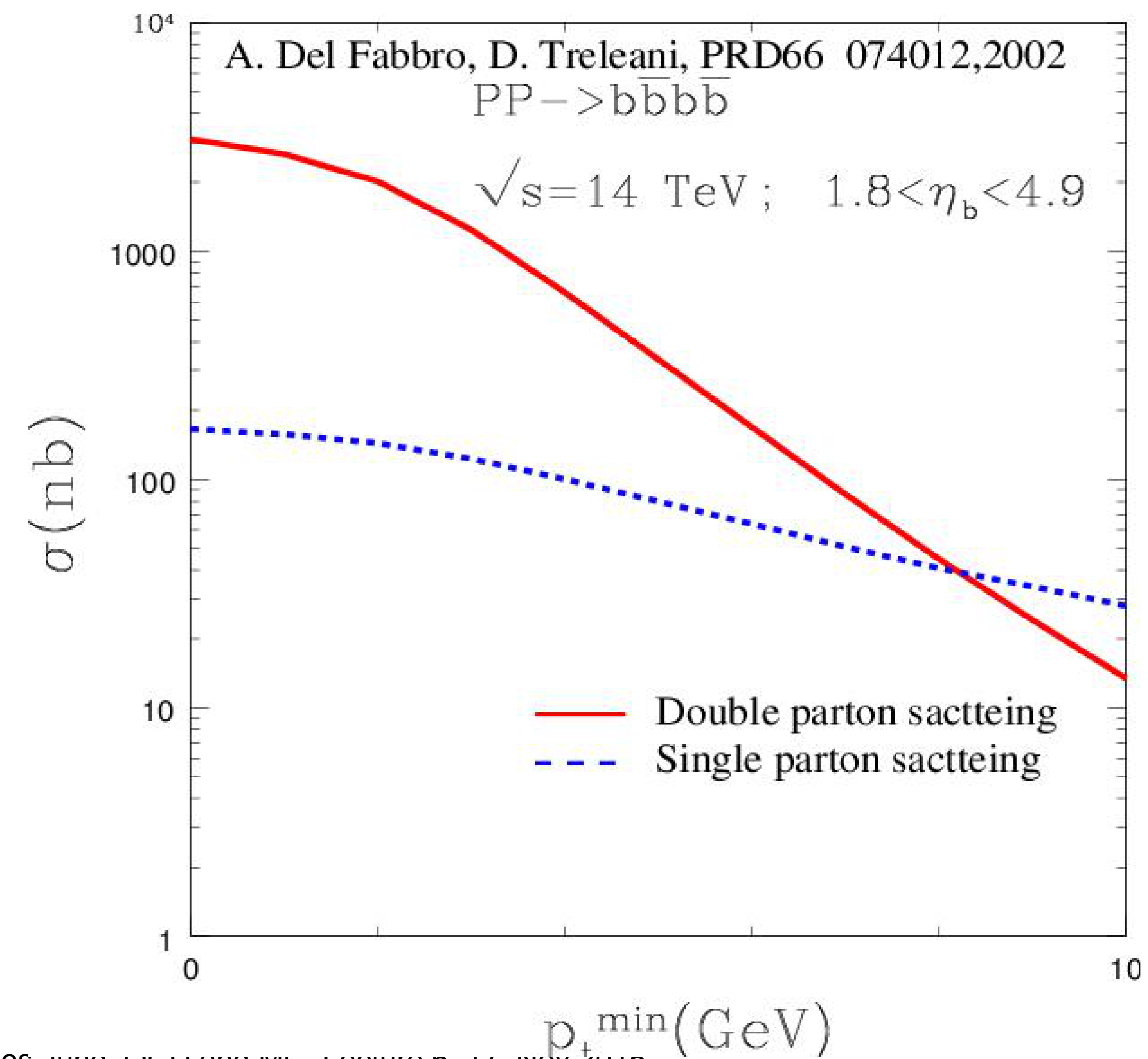
- xsection for $p + p \to b\bar{b}b\bar{b}$

single parton exchange (SP)

$$\sigma^{SP} \sim f^2 \hat{\sigma}(2 \to 4)$$

double parton exchange (DP)

$$\sigma^{DP} \sim f^4 \hat{\sigma}^2(2 \to 2)$$



- PYTHIA predictions:

$$\sigma^{DP} = 0.8 \cdots 11.1 \ \ \mu b$$

➔ Depending on model for underlying event/multi-parton interactions...

Multi-Parton Interactions at LHC

- Higgs: $p + p \to W + H + X$

  with $W \to l\nu, \quad H \to b\bar{b}$

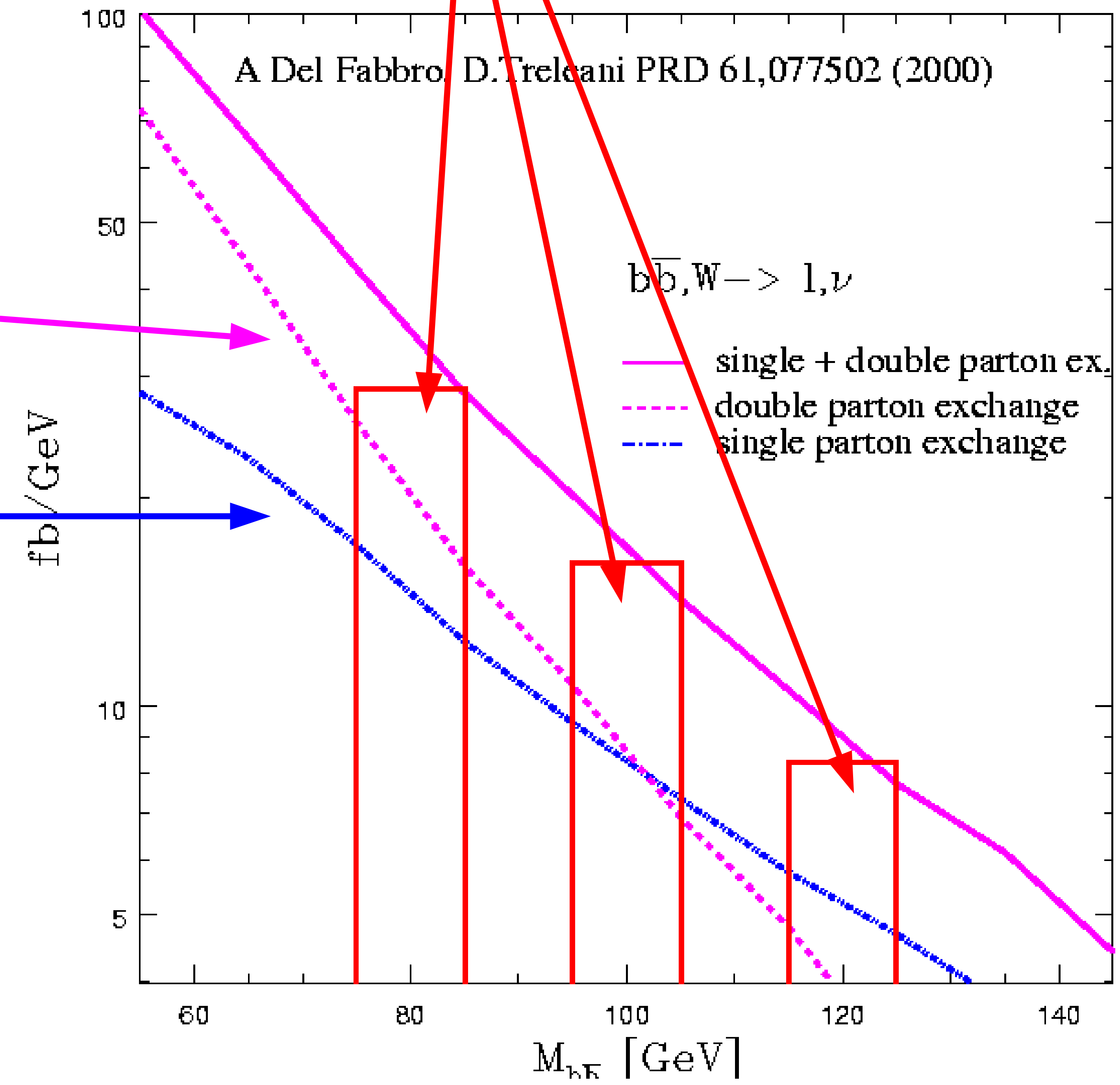
- Double parton scattering:

➔

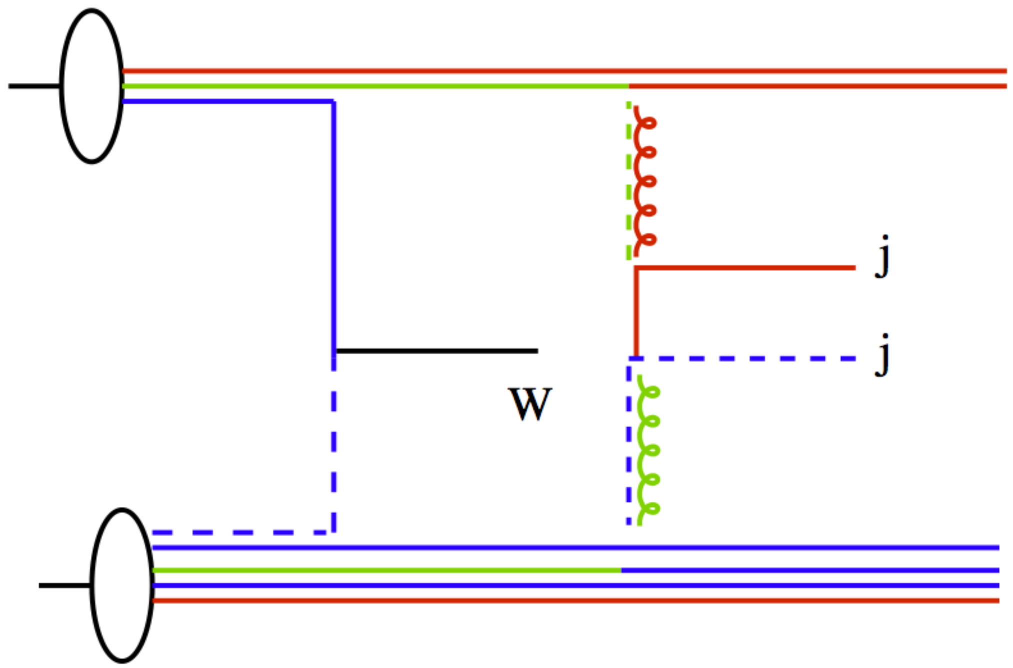
$$p + p \to b\bar{b}X$$
$$p + p \to W + X$$

$$p + p \to W + b\bar{b} + X$$

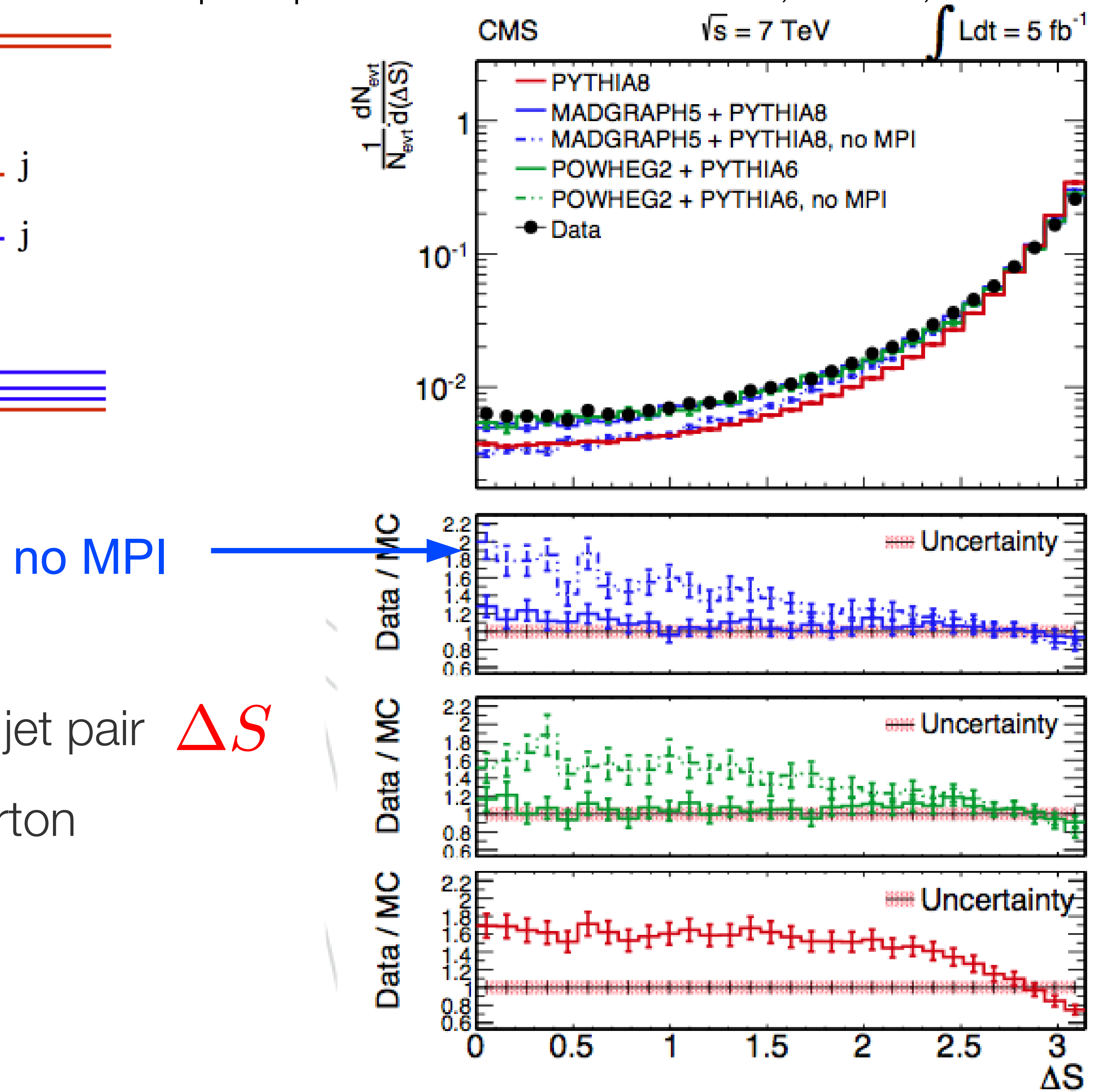
$$p + p \to W + H + X$$



Hard multi - parton Interactions

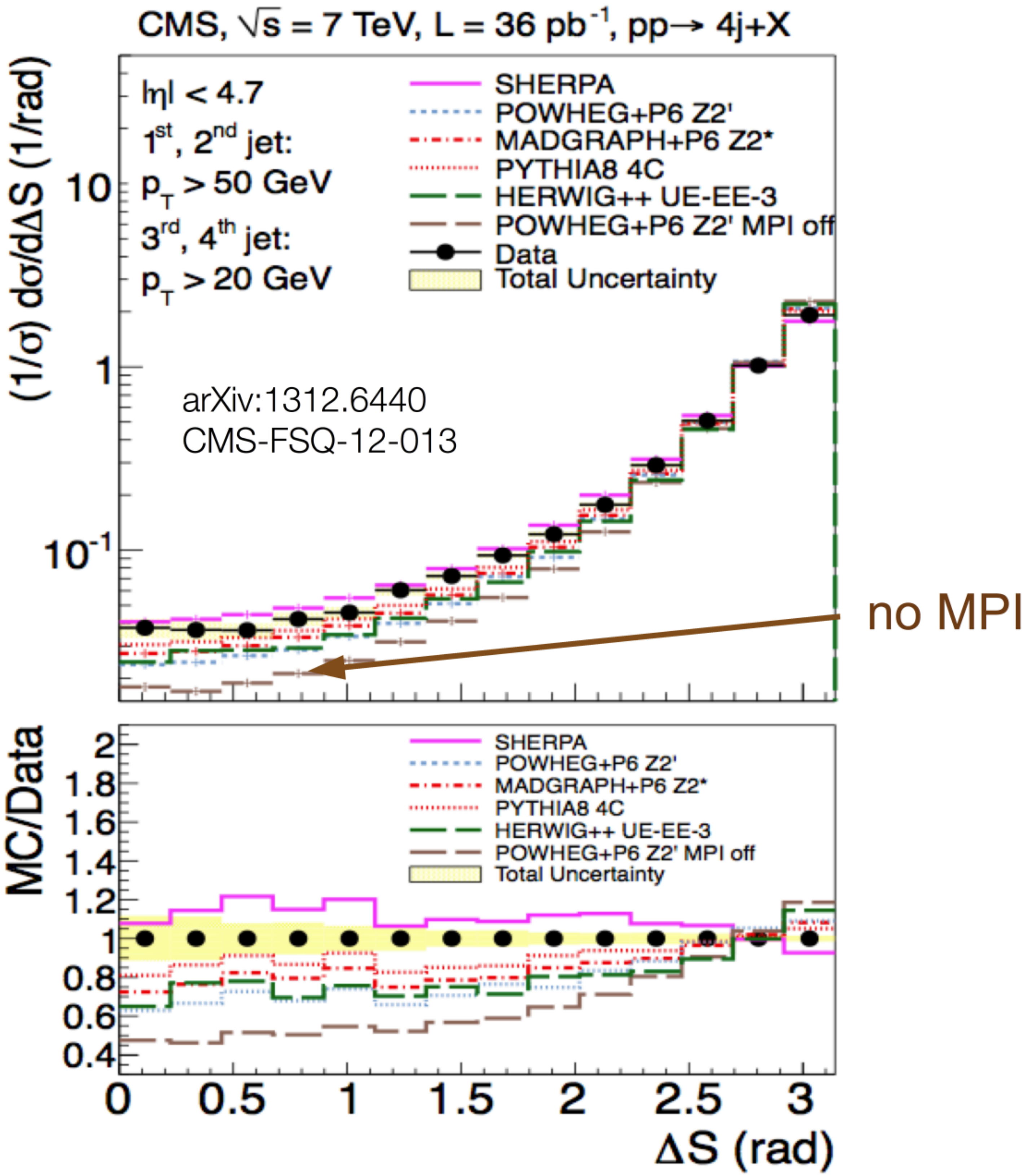


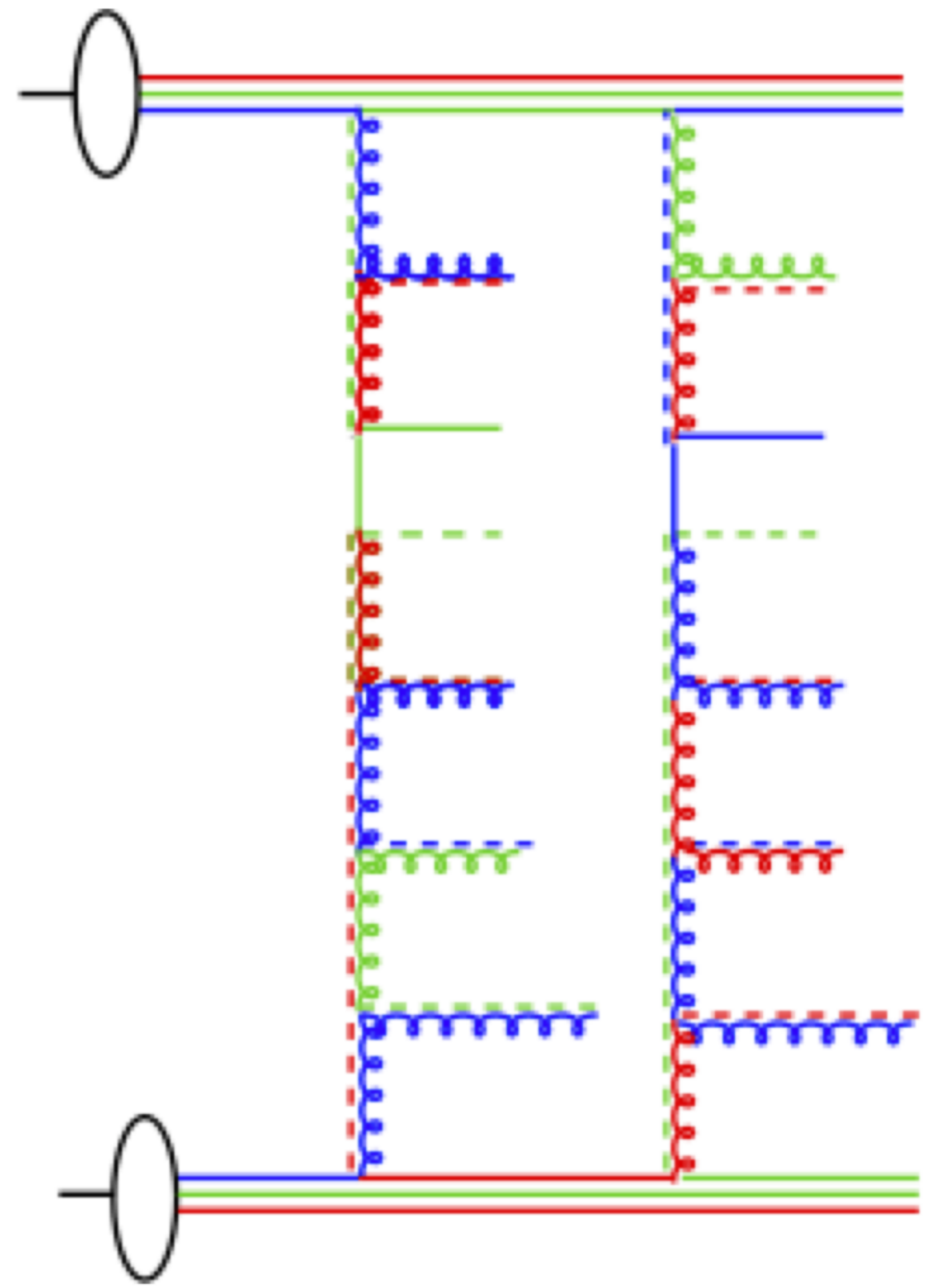
CMS Coll Study of double parton scattering using W + 2-jet events in proton-proton collisions at √s = 7 TeV. JHEP, 1403:032, 2014.



- look at W+2 jets
- angular correlation of W and jet pair ΔS
- clear evidence for double parton scattering

Multiparton interaction at the LHC

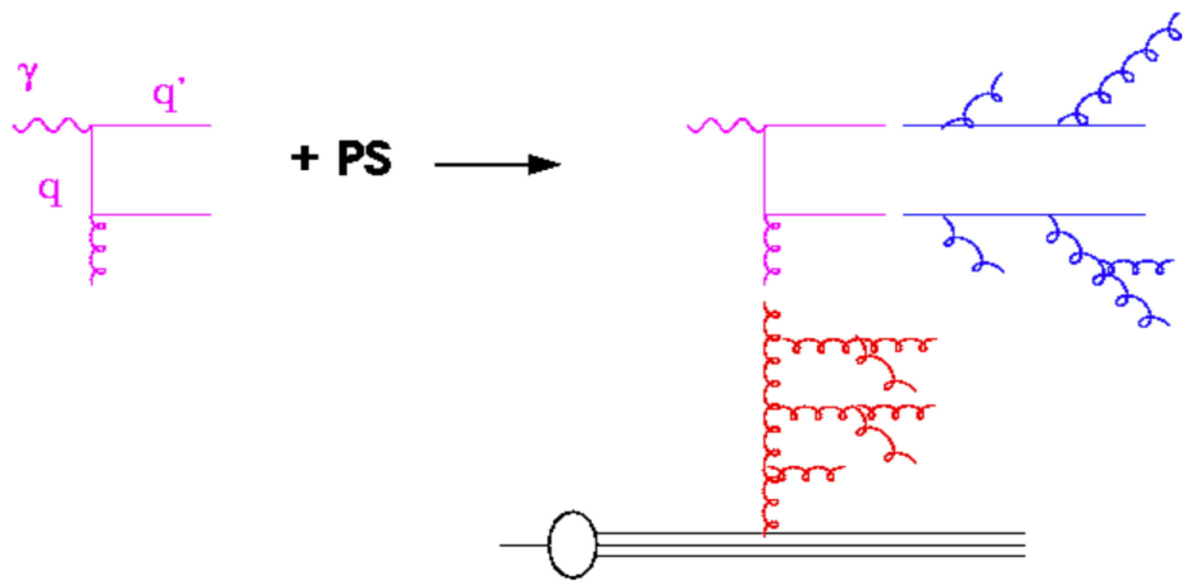




parton densities at small x

- transverse momenta

Inconsistency: example from DIS



- **Collinear approach:** incoming/outgoing partons are on mass shell

  $(\gamma + q)^2 = q'^2$, $-Q^2 + xys = 0 \rightarrow x = Q^2/(ys)$

- **BUT** final state radiation:

  $(\gamma + q)^2 = q'^2$, $-Q^2 + xys = m^2 \rightarrow x = (Q^2 + m^2)/(ys)$

- **AND** initial state radiation:

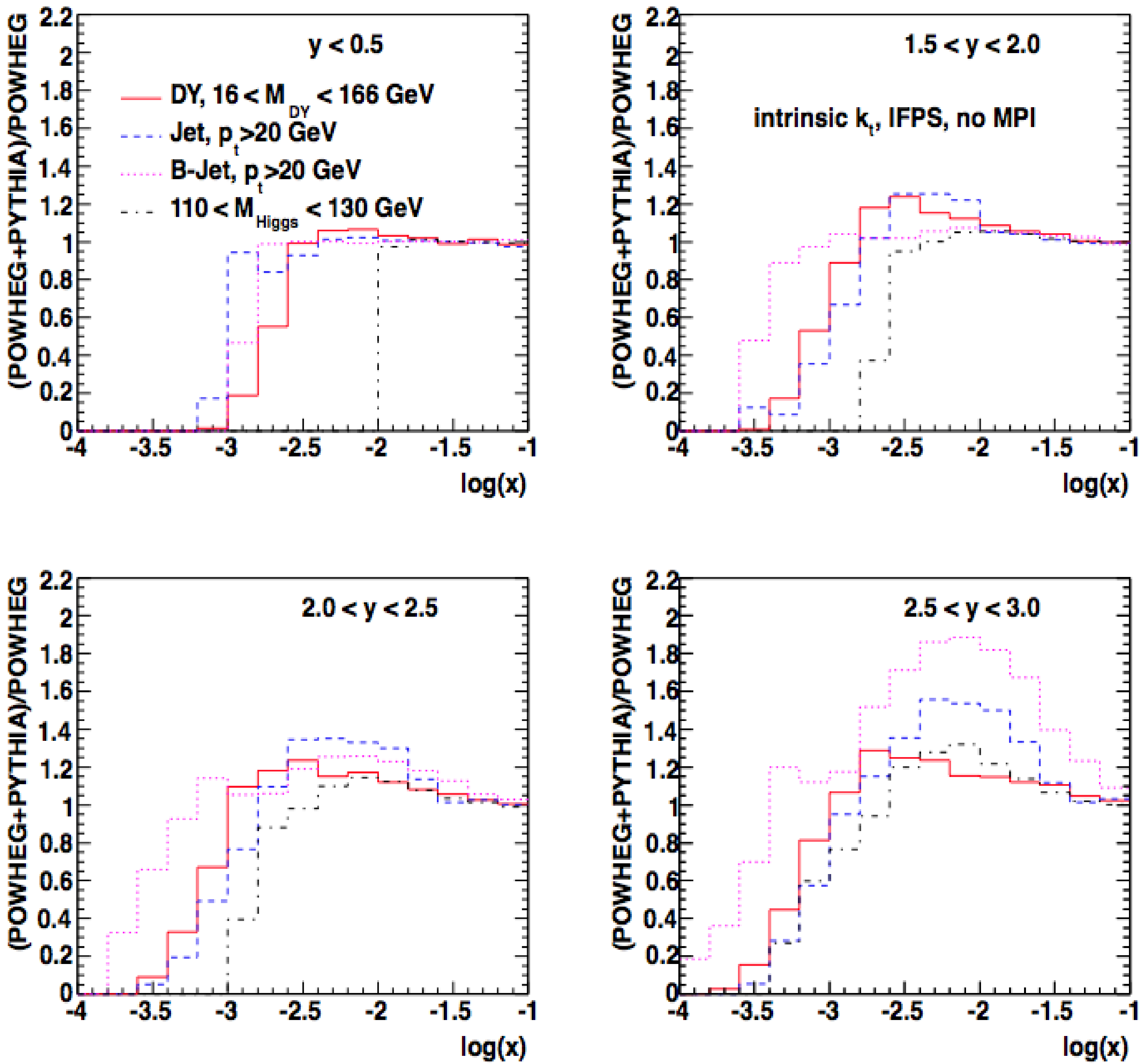
  $(\gamma + q)^2 = q'^2$, $-Q^2 + xys + k^2 = 0 \rightarrow x = (Q^2 - k^2)/(ys)$

Collinear approach: $q'^2 = k^2 = 0$, order by order .....
NLO corrections... better treatment of kinematics... but still not all....

Transverse momentum effects in pp

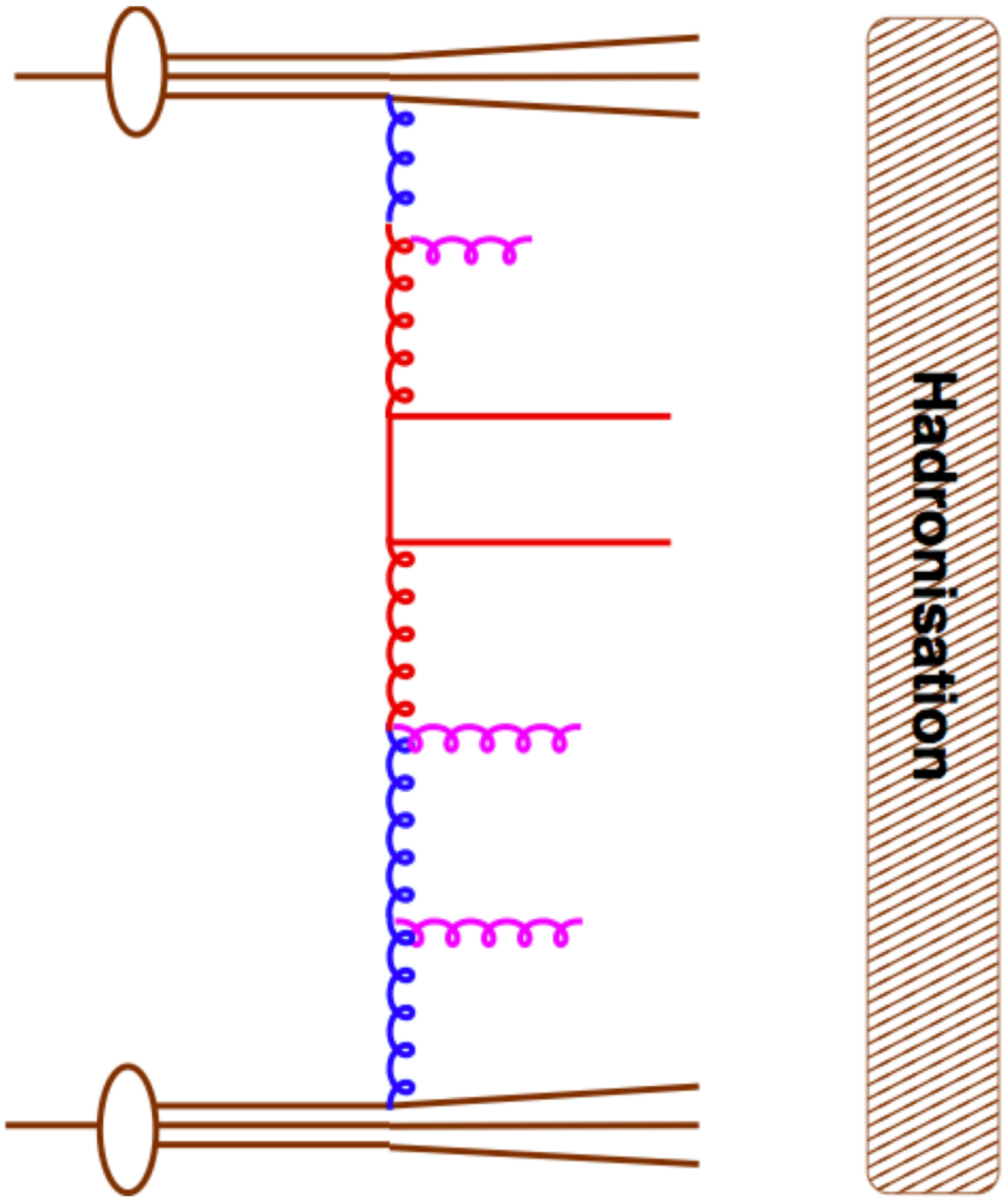
S. Dooling, et al.
Longitudinal momentum shifts, showering and nonperturbative corrections in matched NLO-shower event generators.
Phys.Rev., D87:094009, 2013.

- Transverse momentum effects are relevant for many processes at LHC
- parton shower matched with NLO (POWHEG) generates additional k_t , leading to energy-momentum mismatch
- Transverse momentum effects are visible in high p_t processes, not only at small x



TMDs and the general pp case

- basic elements are:
  - Matrix Elements:
    - ➔ on shell/off shell
  - PDFs
    - ➔ TMD PDFs
  - Parton Shower
    - ➔ angular ordering
- Proton remnant and hadronization



$$\sigma(pp \to q\bar{q} + X) \quad = \quad \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q})$$
$$\times x_{g1} \mathcal{A}(x_{g1}, k_{t1}, \bar{q}) x_{g2} \mathcal{A}(x_{g2}, k_{t2}, \bar{q})$$

But even this is not the full story...

- factorization breaking in $pp \to j_1 j_2 X$

  J. Collins, J.W. Qiu hep-ph 0705.2141

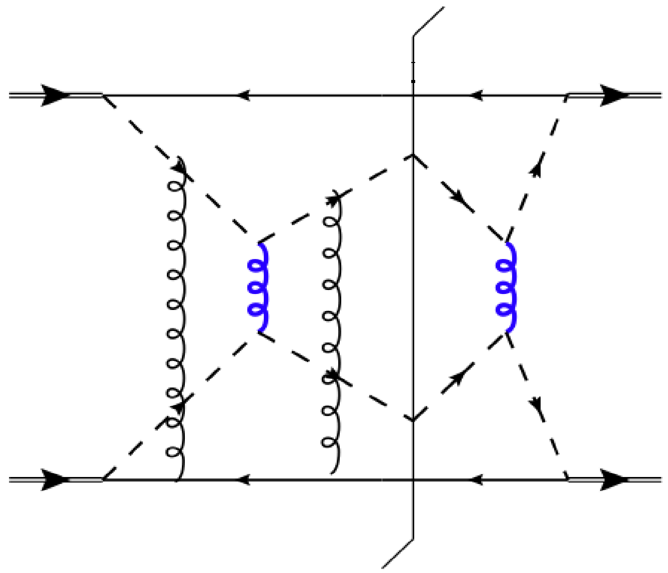
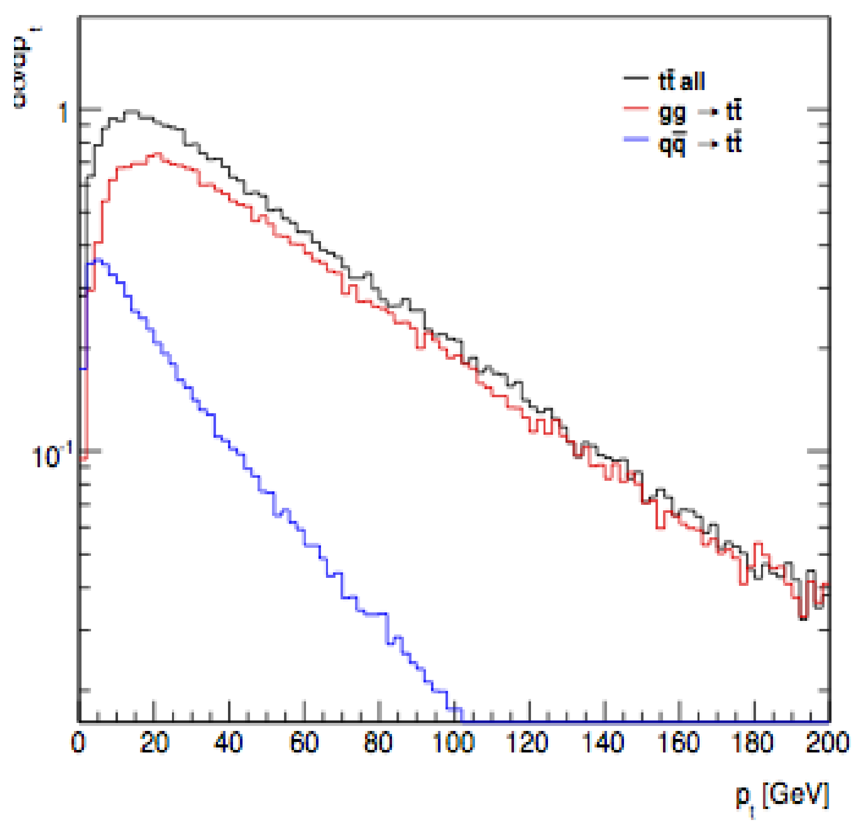


FIG. 8 (color online). The exchange of two extra gluons, as in this graph, will tend to give nonfactorization in unpolarized cross sections.

- factorization breaking also in $t\bar{t}$ -production at large p_t^{top}

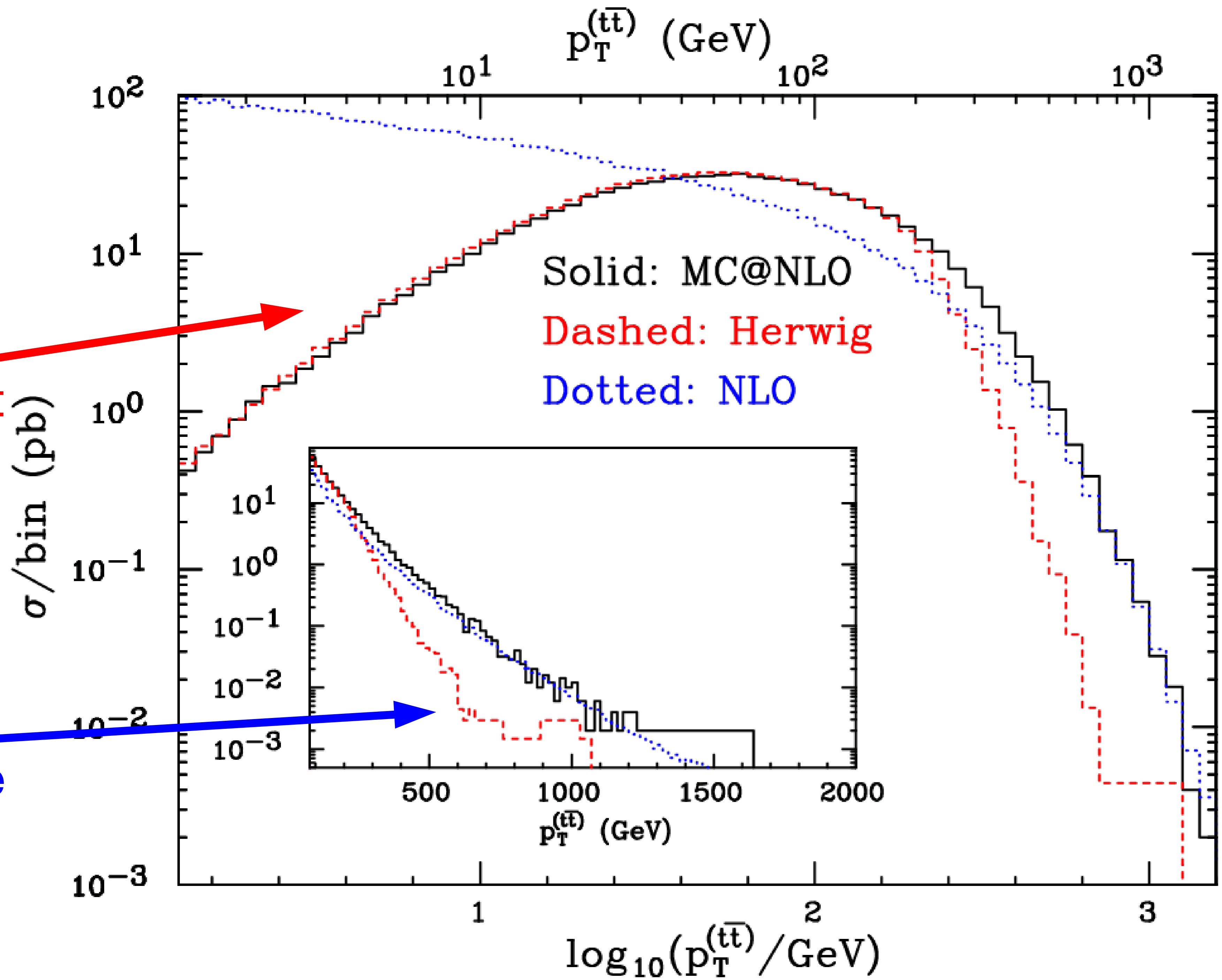
  S. Catani, M. Grazzini, and A. Torre. Transverse-momentum resummation for heavy-quark hadropro- duction. arXiv 1408.4564



Small pt in heavy quark prod.

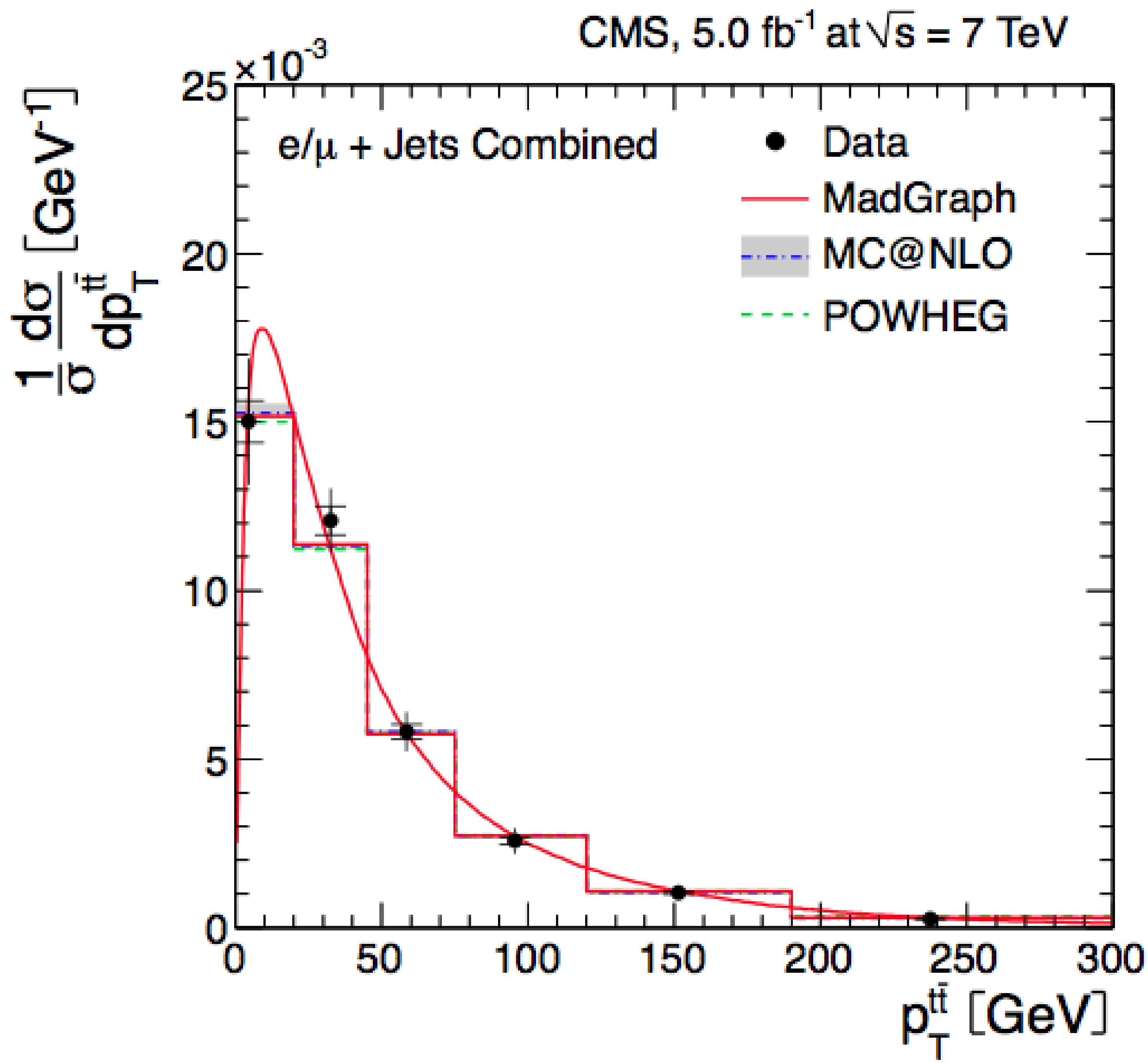
Frixione et al, hep-ph/035252

- Compare fixed NLO calculation of top production with resummed calculation from Monte Carlo
- Similar effects at small pt are observed: Suppression of xsection at small pt
- At large pt, resummation is too small, NLO is bette

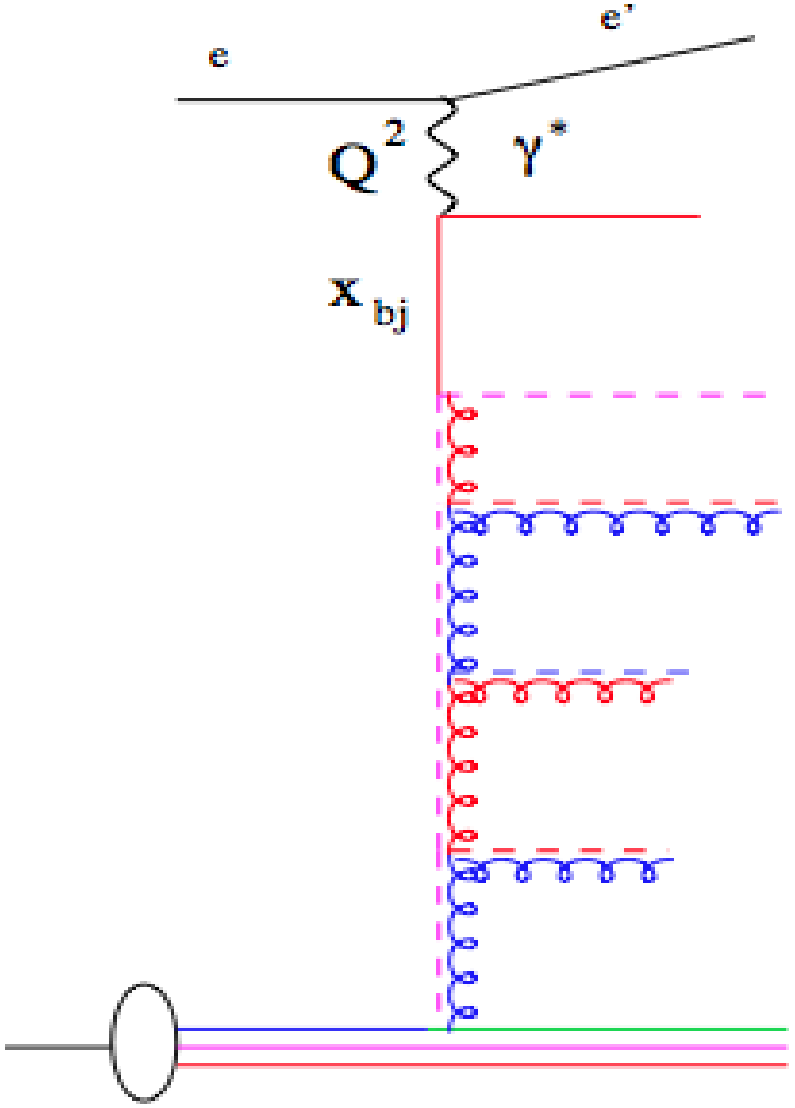


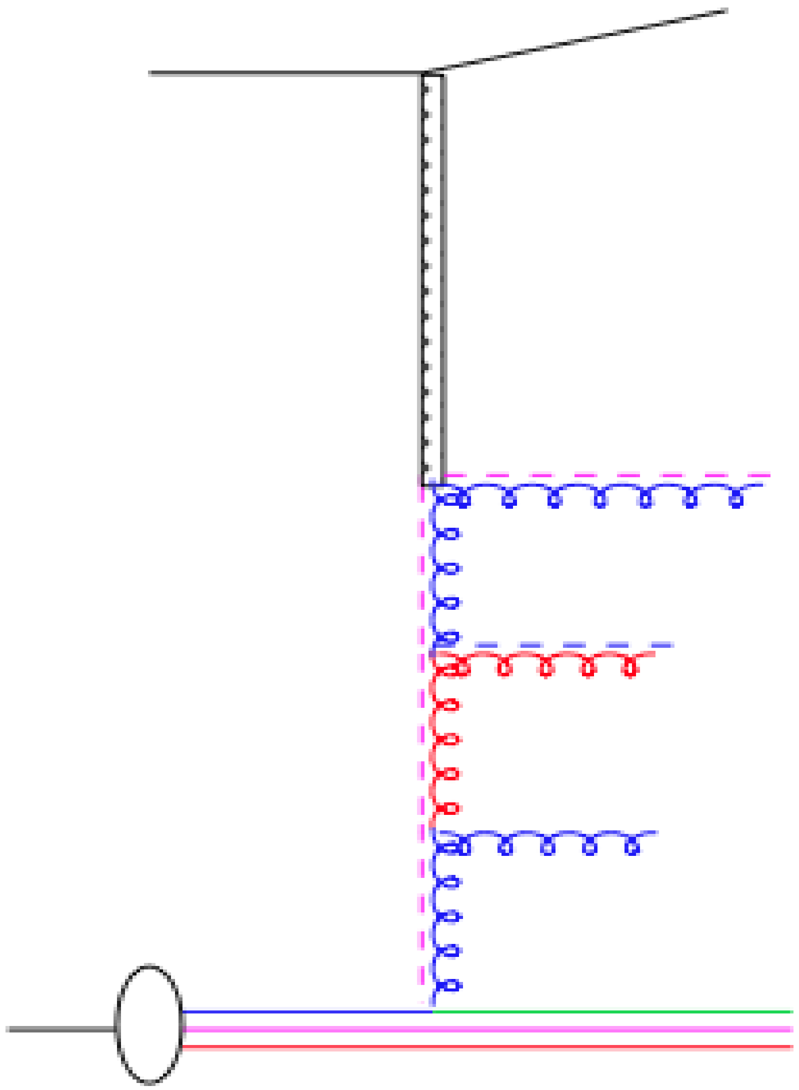
… and the measurements

CMS coll.
Measurement of differential top-quark pair production cross sections in pp collisions at sqrt(s) = 7 TeV
arXiv:1211.2220 EPJ C73 (2013) 2339



Imagine, would could probe gluons directly





Imagine ...

- all standard electro-weak currents couple to quarks:

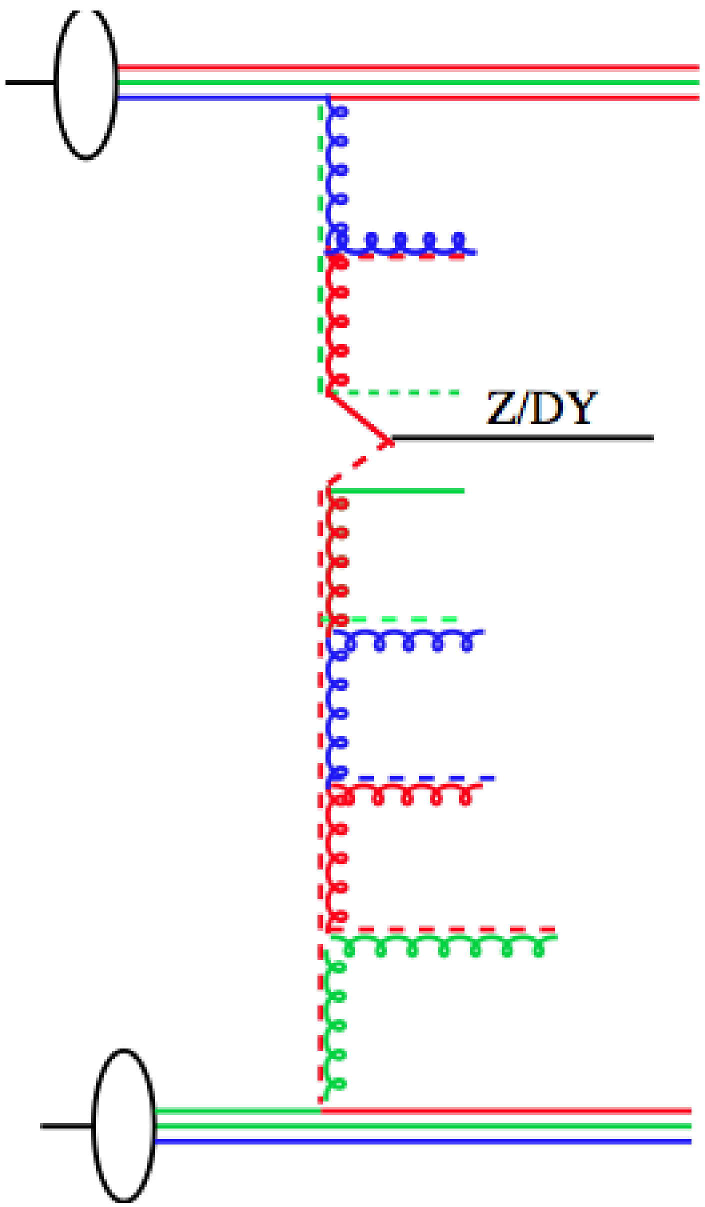
$$\gamma,\ Z_0,\ W$$

  - structure function of quarks are well measured in DIS scattering, as well as in DY production
  - structure function of gluons, as well as properties of gluons are measured only indirectly via quark

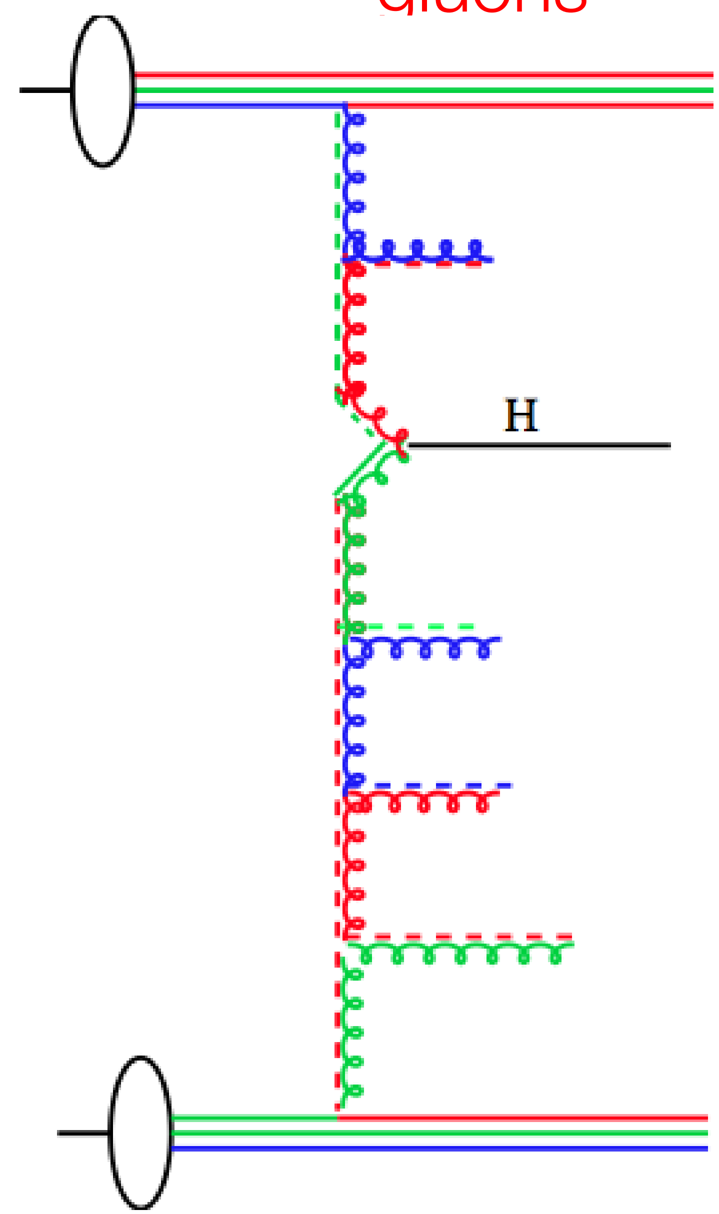
Imagine ...

- all standard electro-weak currents couple to quarks:

$$\gamma, Z_0, W$$



- Higgs is special:
    - in heavy top limit, couples directly to gluons

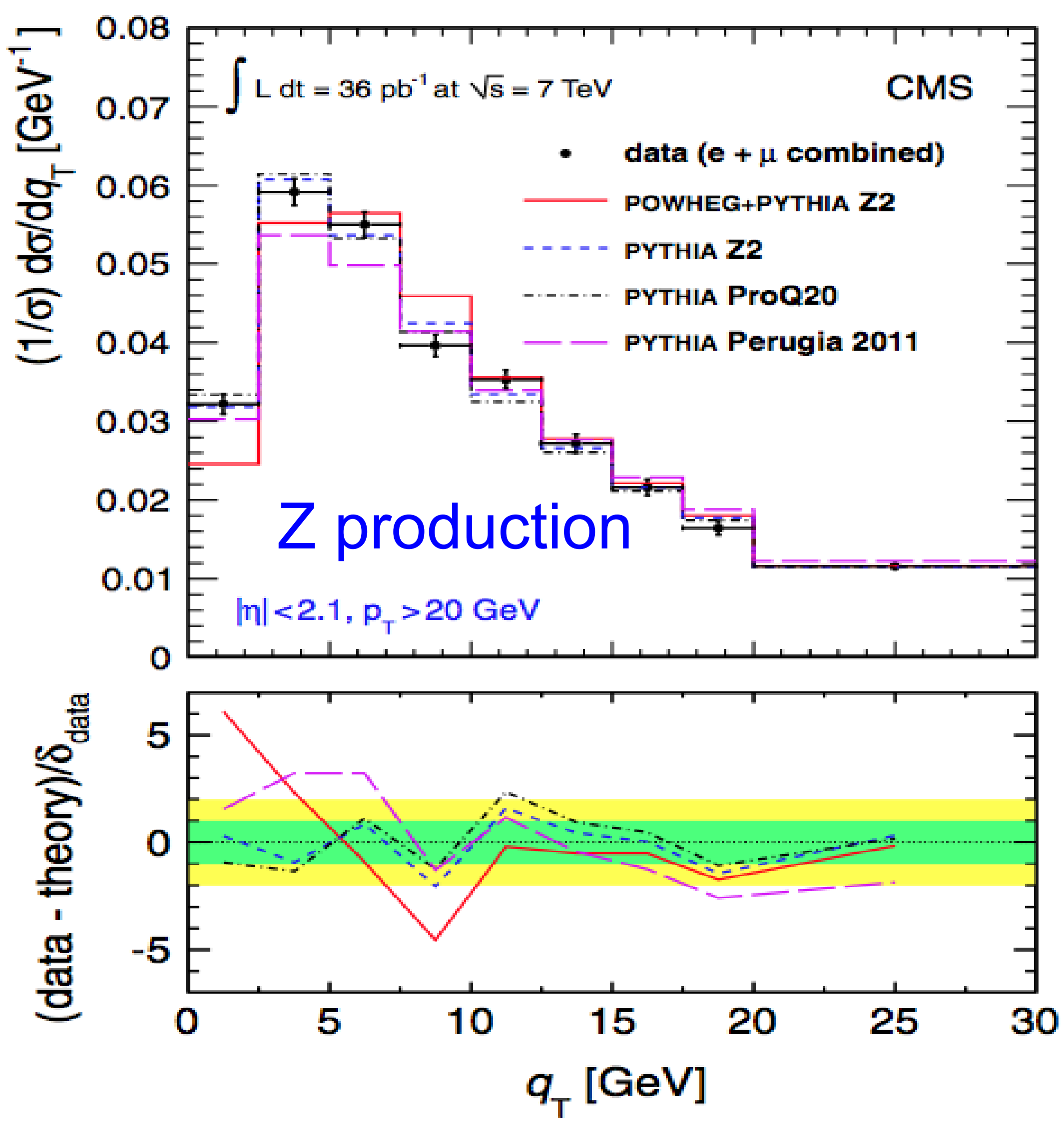


QCD options at high luminosity LHC

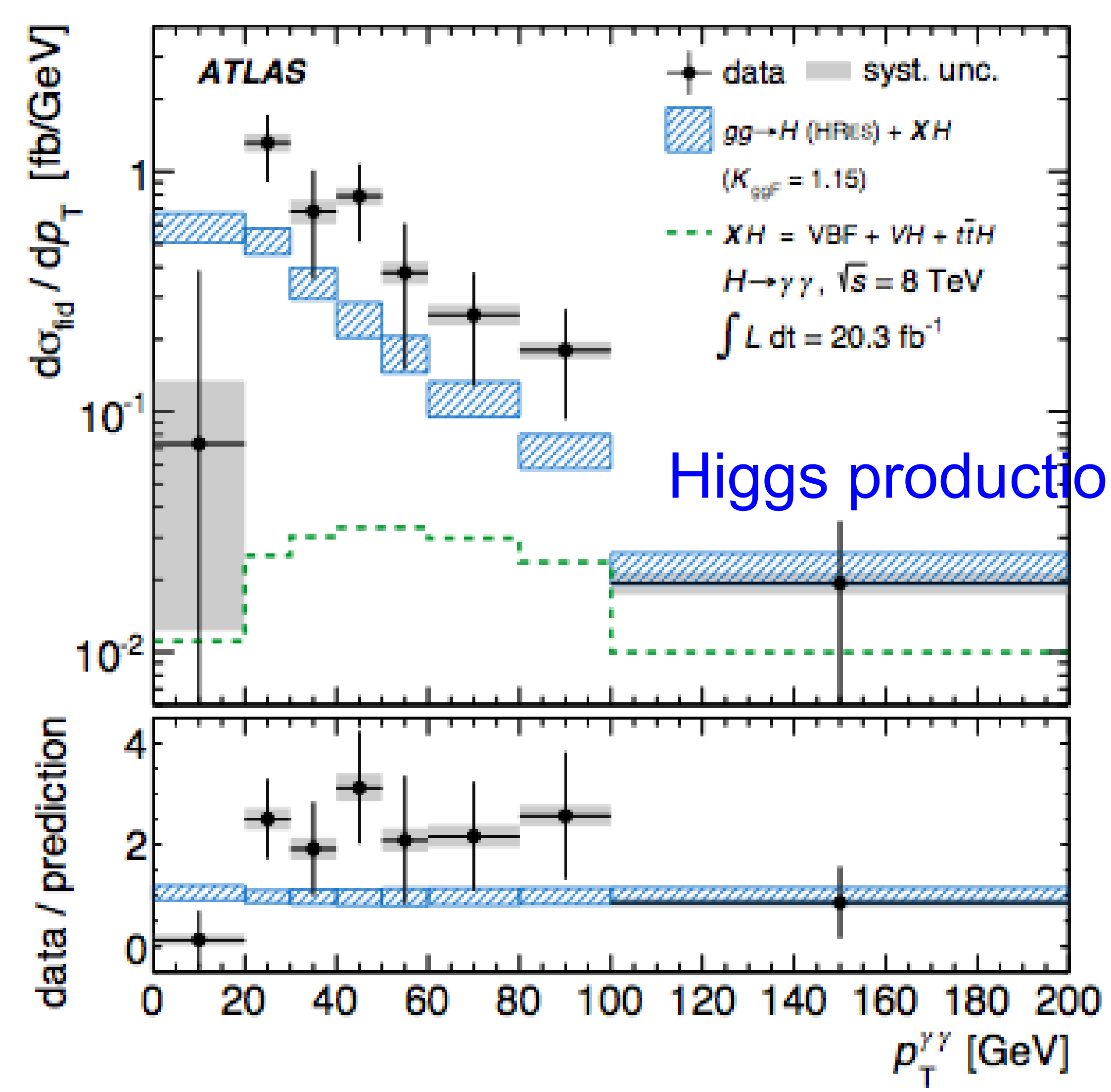
With Higgs, we have a new and exciting result, which opens up a completely new world for QCD studies:

- gluon process with color singlet final state at large masses:

CMS Coll., PRD 85, 032002 (2012)



Differential cross sections of the higgs boson measured in the diphoton decay channel using 8 TeV pp collisions. ATLAS arXiv 1407.4222

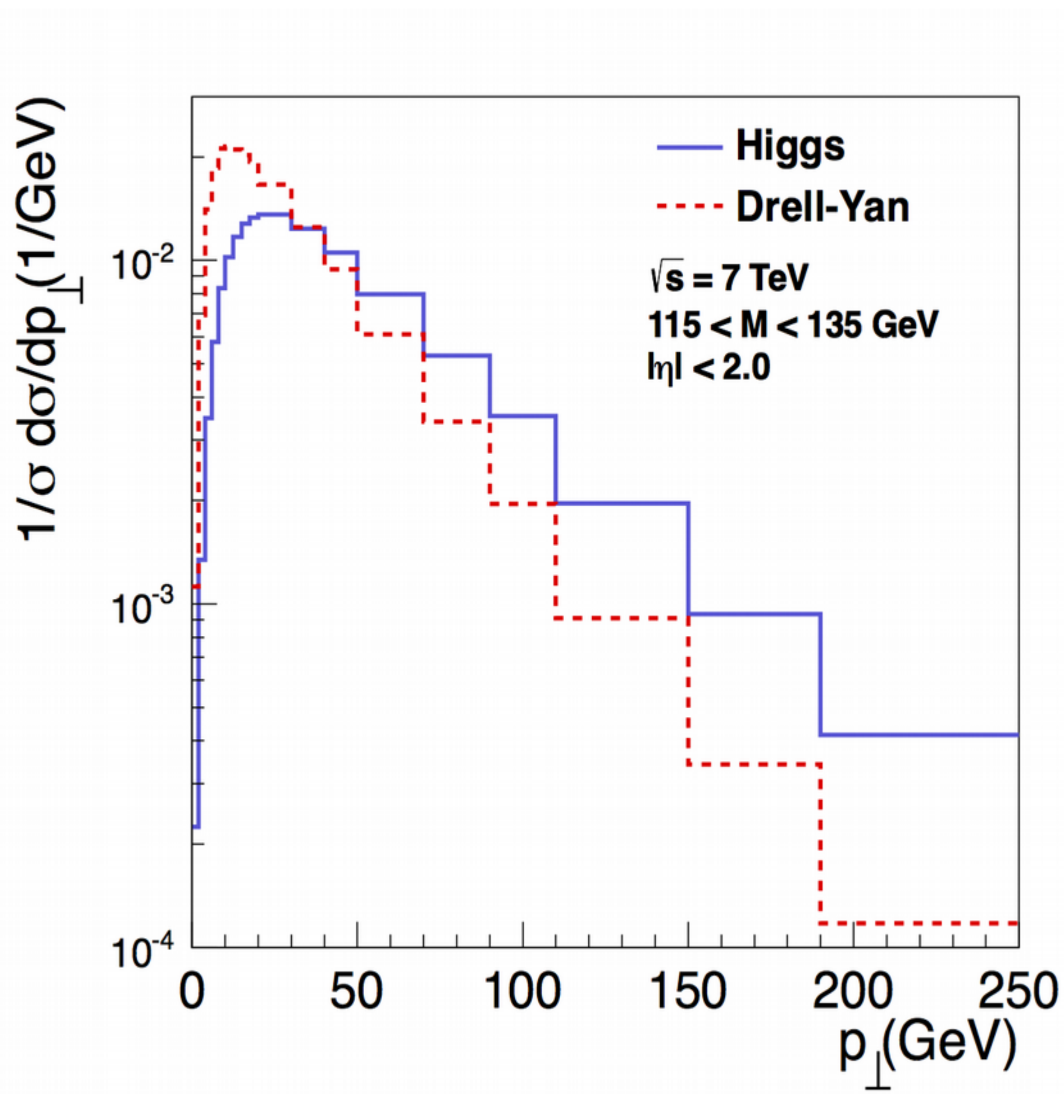


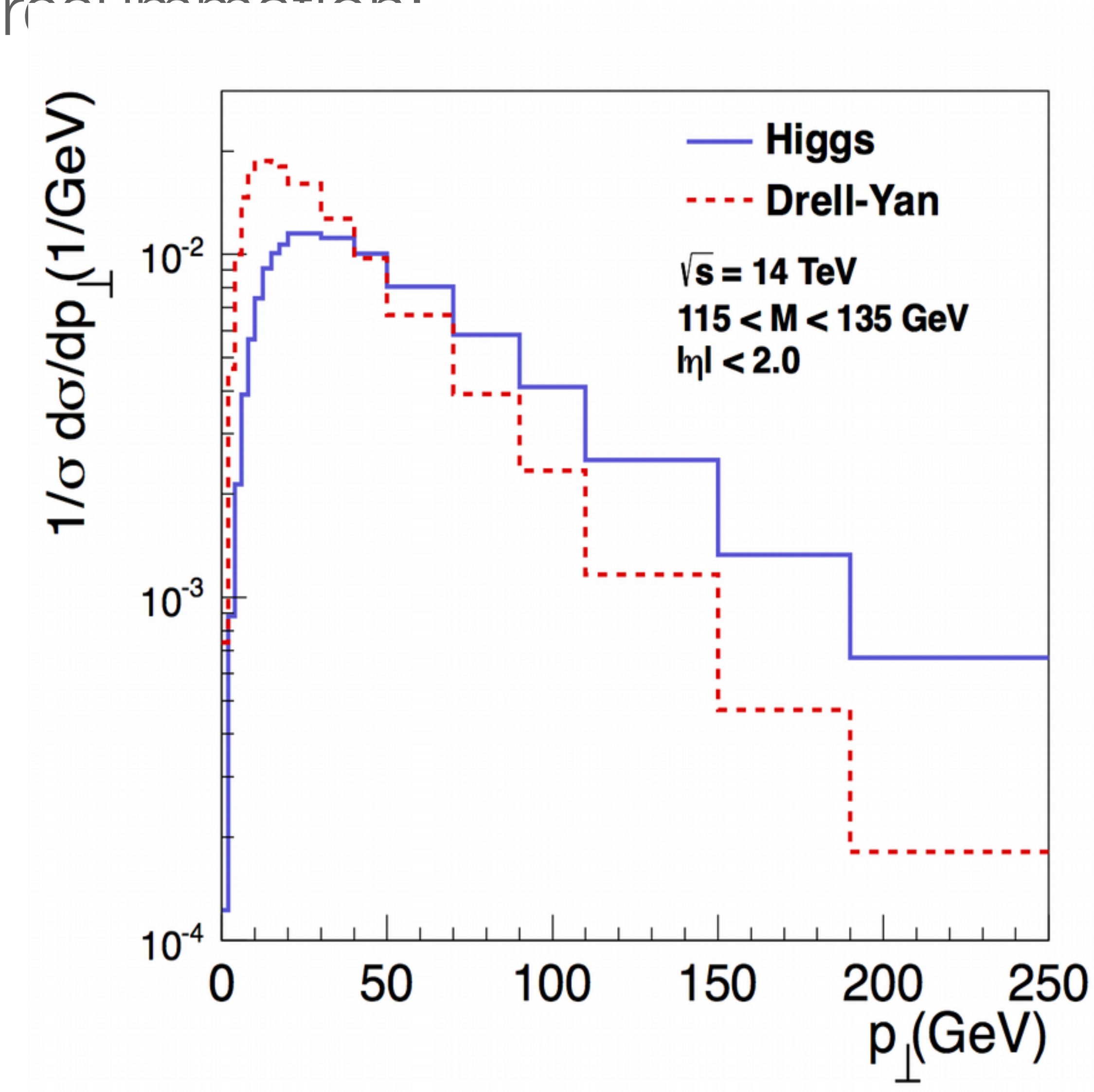
Higgs as a gluon trigger

Start new QCD program with Higgs as gluon trigger

P. Cipriano, S. Dooling, A. Grebenyuk, P. Gunnellini, F. Hautmann, H. Jung, and P. Katsas. Higgs boson as a gluon trigger. Phys. Rev. D, 88:097501, Nov 2013. arXiv:1308.1655

- comparison with DY production at same mass range
- p_T spectrum of DY and Higgs:





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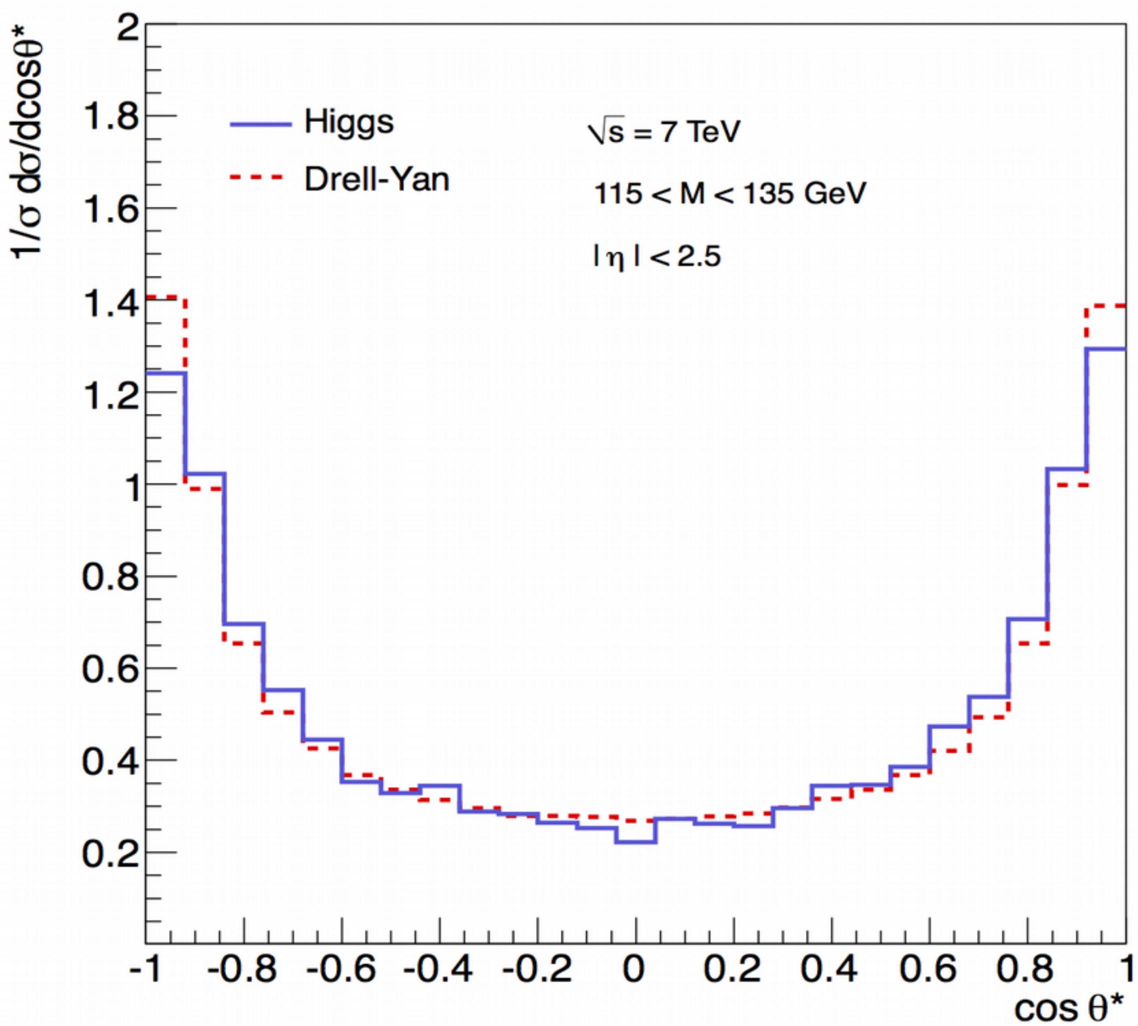
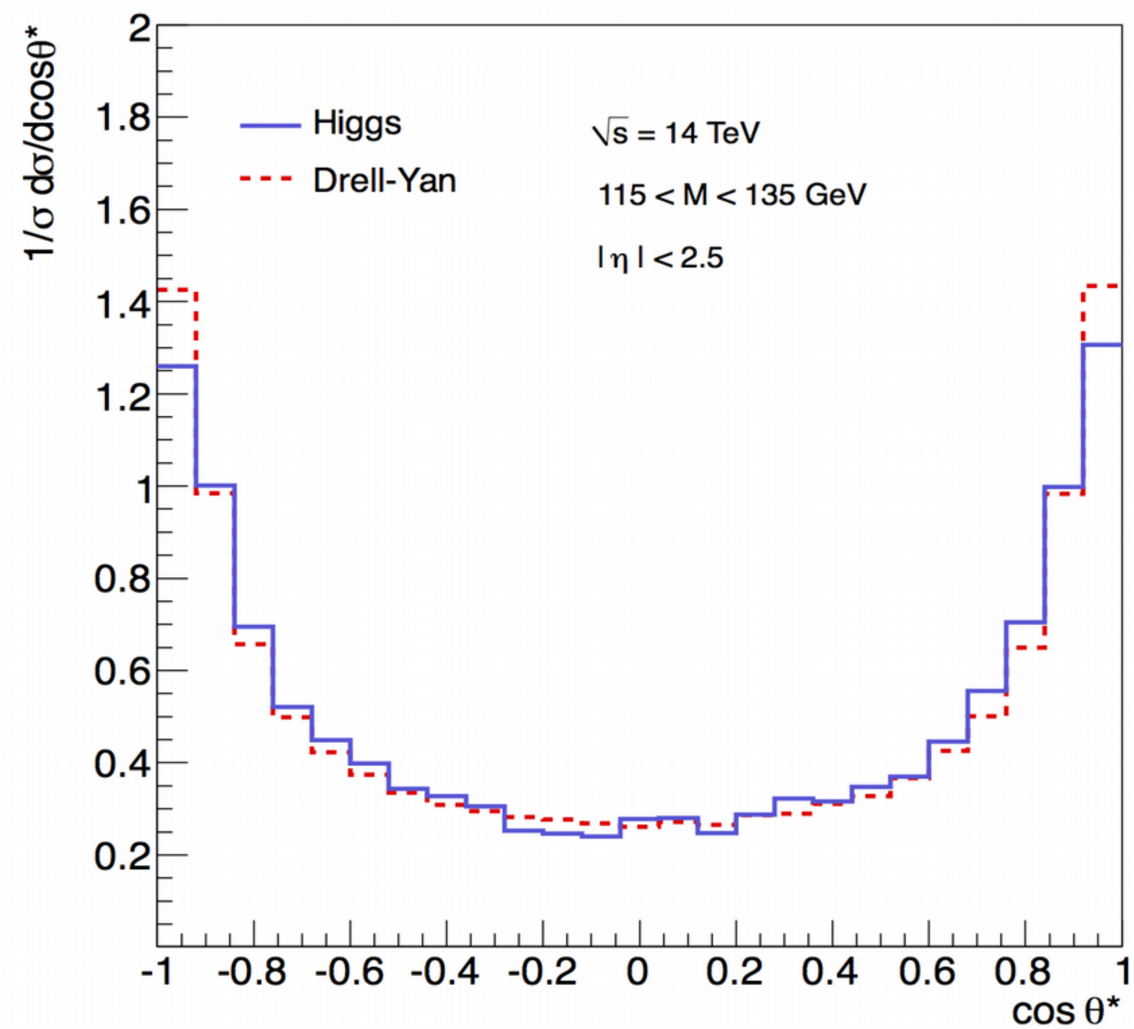
- comparison with DY production as same mass range
- jet + DY / Higgs: in rest-frame sensitivity to spin-coupling to gluons - vanishing effect of quark vrs gluon propagator





Challenge in QCD – another example

High Energy Description of Processes with Multiple Hard Jets
Jeppe R. Andersen. Jennifer M. Smillie.
Nucl.Phys.Proc.Suppl. 205-206 (2010) 205-210, 1007.4449

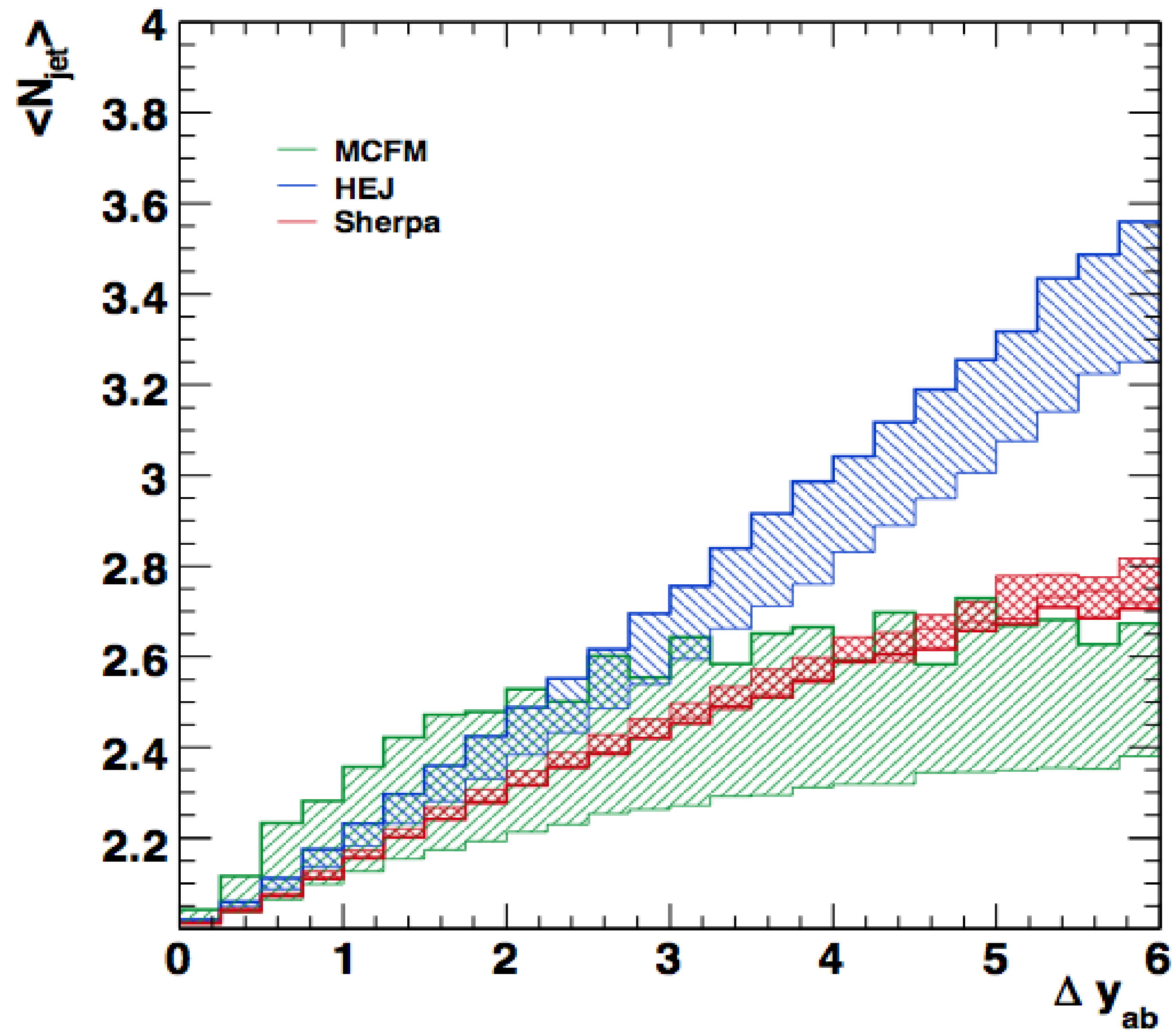
- Higgs + jet production
  - as fct of $\Delta\, y$ jet multiplicity must increase
  - similar to dijet case
- Measure at fixed $m = 125\, GeV$:

$$\frac{dn}{d\Delta y}_{Higgs} - \frac{dn}{d\Delta y}_{DY}$$

- pileup and UE effects cancel
- isolate gluon contribution

$$pp \rightarrow h + \text{ 2 jets (+ n jets)}$$

$$\sqrt{s} = 10 \text{ TeV}, \; p_T > 40 \text{ GeV}$$



There are many open questions in QCD at highest energies and at highest scales ….

Your ideas, imagination and help is very much needed !

The End

.... what you should have learned

- Lecture:
  - QCD is still a interesting and challenging field
  - basic QCD calculations
  - important role of gluons, which comes from gluon self-coupling
  - understanding of parton evolution equations in terms of parton radiation
  - importance of “soft” gluon resummation
- Exercises:
  - basic Monte Carlo techniques
  - MC integration and generation of variables according to distributions
  - solution of parton evolution equation with MC technique
  - advantage of MC technique to solve complex problems like multiparton radiation (example pt spectrum of Drell Yan)

.... what you should have learned

Have a good time,

and enjoy when

gambling with Monte Carlos