Multiparton interactions: Theory and experimental findings

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HELMHOLTZ
GEMEINSCHAFT

DESY

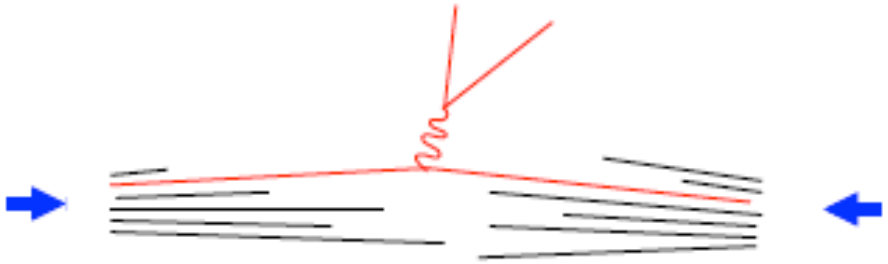
Hadron-hadron collisions

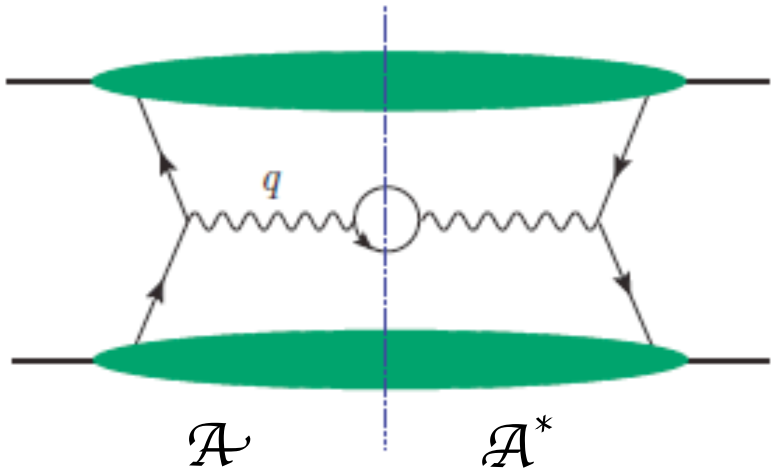
- standard description based on factorization formulae

  cross sect = parton distributions × parton-level cross sect

  example: Z production

  $pp \to Z + X \to \ell^+\ell^- + X$





- factorization formulae are for inclusive cross sections $pp \to Y + X$
  where Y = produced in parton-level scattering, specified in detail
  X = summed over, no details

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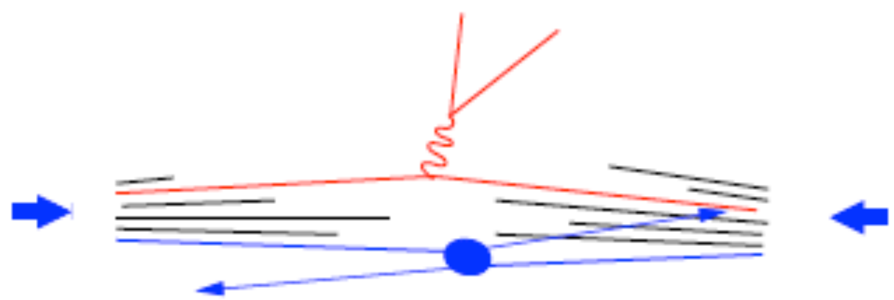
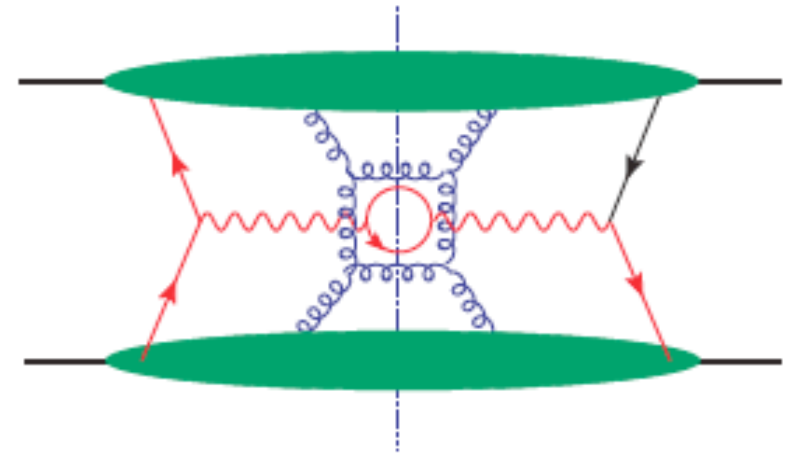




- factorization formulae are for inclusive cross sections $pp \to Y + X$
  where Y = produced in parton-level scattering, specified in detail
  X = summed over, no details
- have also interactions between "spectator" partons
  their effects cancel in inclusive cross sections thanks to unitarity
  but they affect the final state (namely X)

Multiparton interactions (MPI)

- secondary (and tertiary etc.) interactions generically take place in hadron-hadron collisions
- predominantly low-p_T scattering
  $\rightsquigarrow$ underlying event (UE)
- at high collision energy (Tevatron, LHC) can be hard
  $\rightsquigarrow$ multiple hard scattering

"MPI" used either for mult. hard scatt. or for hard+soft

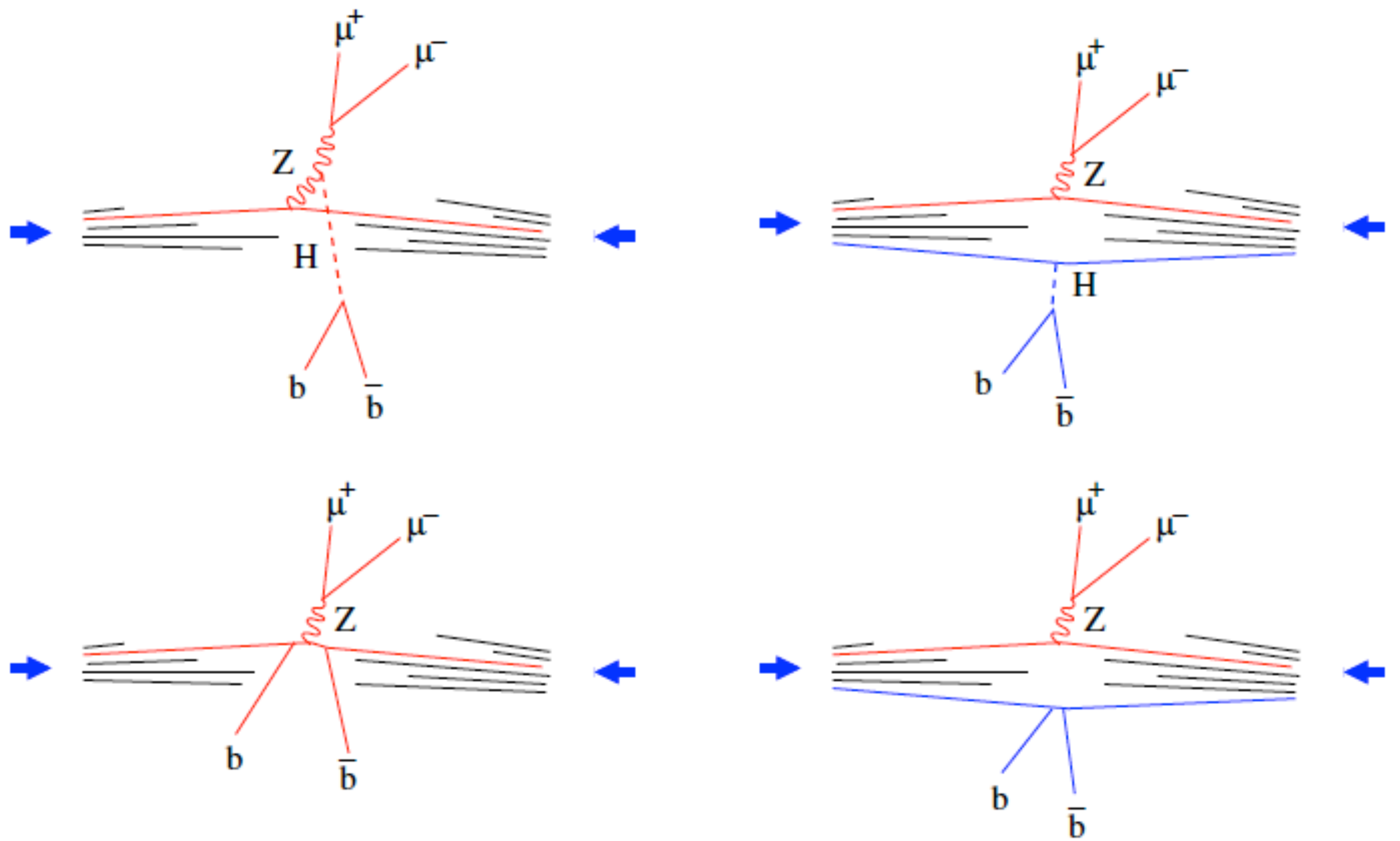
- many studies:
  theory: phenomenological studies, theoretical foundations (recent activity)
  experiment: ISR, SPS, HERA (photoproduction), Tevatron, LHC
  Monte Carlo generators: Pythia, Herwig++, Sherpa
- expected to be important for many processes at LHC

see e.g. workshops: `http://mpi11.desy.de`; MPI@LHC 2012, CERN

Relevance for LHC

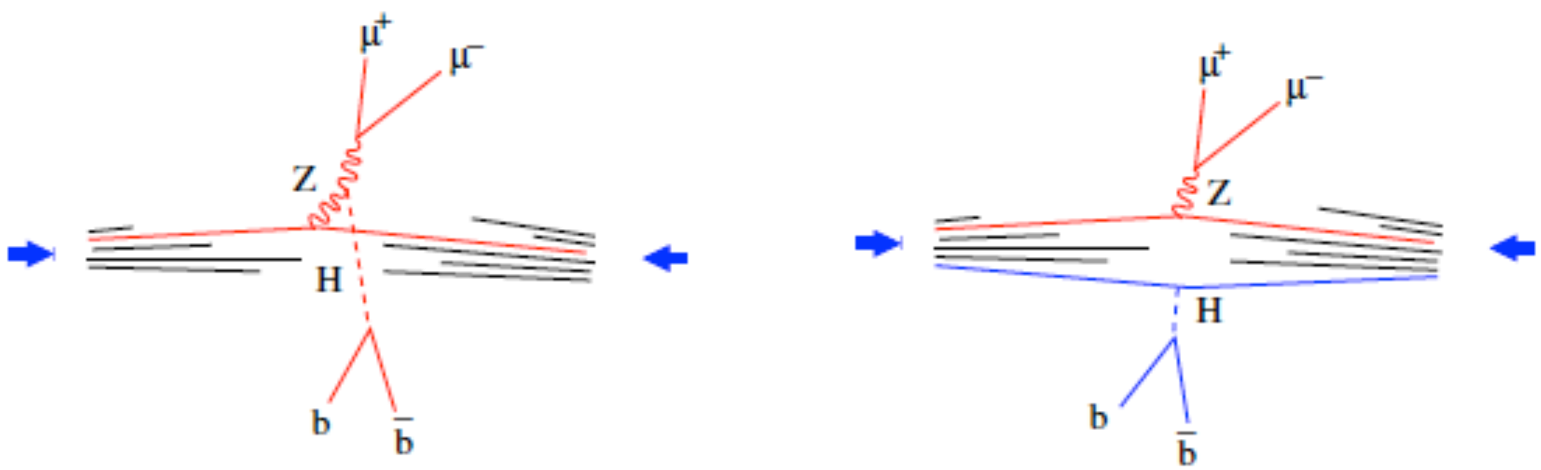
example: $pp \to H + Z \to b\bar{b} + Z$ — Del Fabbro, Treleani 1999

- multiple interactions contribute to signal and background



analogous for $pp \to H + W \to b\bar{b} + W$ — study for Tevatron: Bandurin et al,

Double vs. single hard scattering



- double hard scattering:
  net p_T of produced system (Z or $b\bar{b}$ pair) $\ll$ hard scale Q (e.g. M_Z)
- single hard scattering:
  p_T distribution up to values $\sim Q$
- no generic suppression for transv. mom. $\ll Q$:

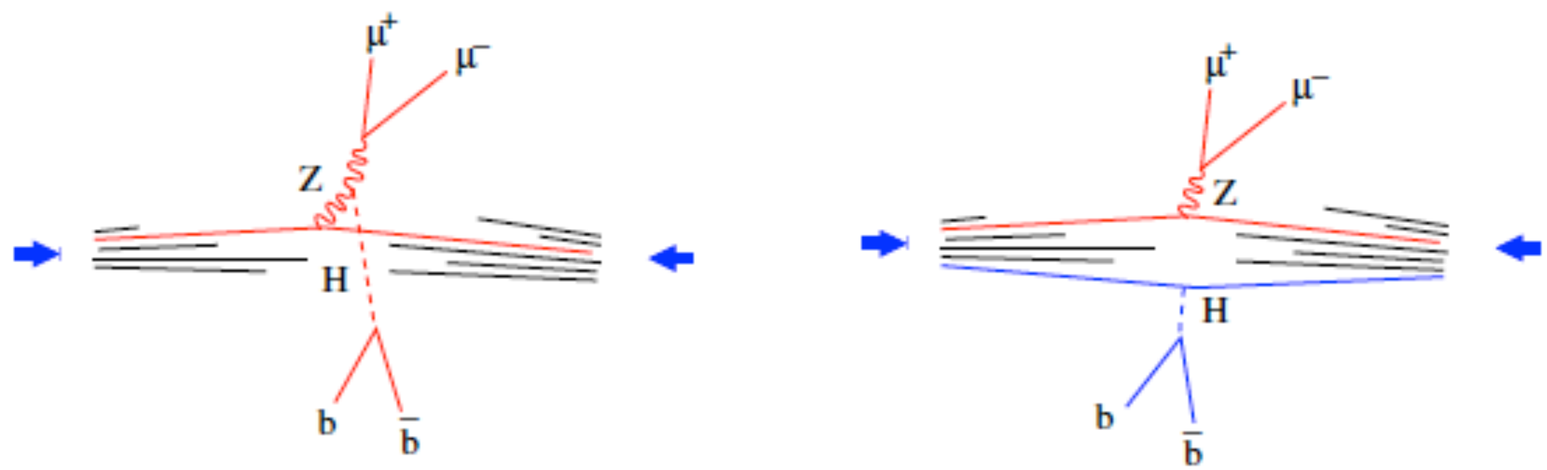
$$\frac{d\sigma_{\text{single}}}{d^2 p_{T,Z}\, d^2 p_{T,b\bar{b}}} \sim \frac{d\sigma_{\text{double}}}{d^2 p_{T,Z}\, d^2 p_{T,b\bar{b}}} \sim \frac{\Lambda^2}{Q^2}$$

but since single scattering populates larger phase space :

$$\sigma_{\text{single}} \sim \frac{1}{Q^2} \gg \sigma_{\text{double}} \sim \frac{\Lambda^2}{Q^4}$$

MD, Schäfer 2011; Blok, Dokshitzer, Frankfurt, Strikman 2011

Double vs. single hard scattering



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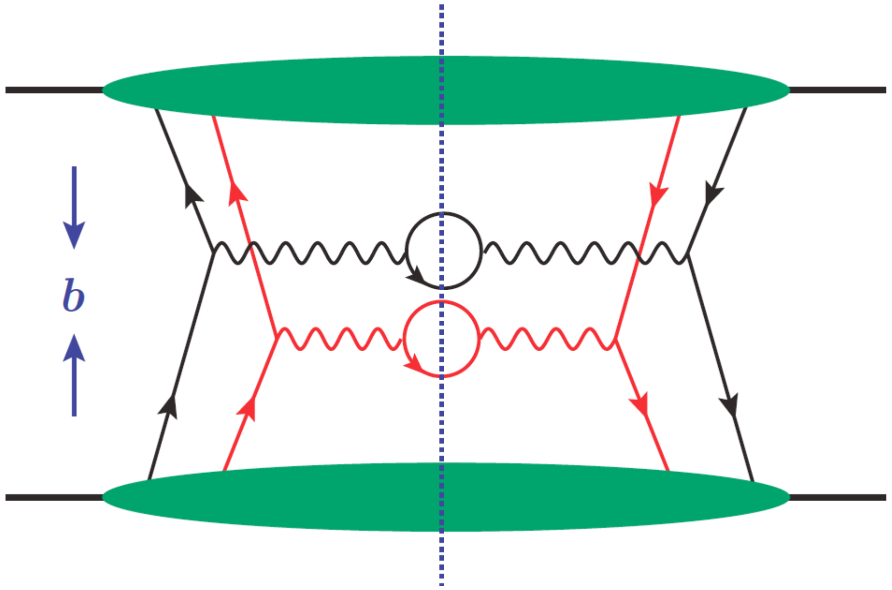
at small x double scattering enhanced due to growth of parton densities

MD, Schäfer 2011; Blok, Dokshitzer, Frankfurt, Strikman 2011



Double parton scattering: cross section formula

Paver, Treleani 1982, 1984; Mekhfi 1985, . . . , MD, Ostermeier, Schäfer 2012

$$\frac{d\sigma_{\text{double}}}{dx_1\, d\bar{x}_1\, dx_2\, d\bar{x}_2} = \frac{1}{C}\, \hat{\sigma}_1\, \hat{\sigma}_2 \int d^2\boldsymbol{b}\; F(x_1, x_2, \boldsymbol{b})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{b})$$

$C =$ combinatorial factor
$\hat{\sigma}_i =$ parton-level cross section
$F(x_1, x_2, \boldsymbol{b}) =$ double parton distribution (DPD)
$\boldsymbol{b} =$ transv. distance between partons

- follows from Feynman graphs and hard-scattering approximation
  no semi-classical approximation required
- can make $\hat{\sigma}_i$ differential in further variables (e.g. for jet pairs)
- can extend $\hat{\sigma}_i$ to higher orders in α_s
  get usual convolution integrals over x_i in $\hat{\sigma}_i$ and F

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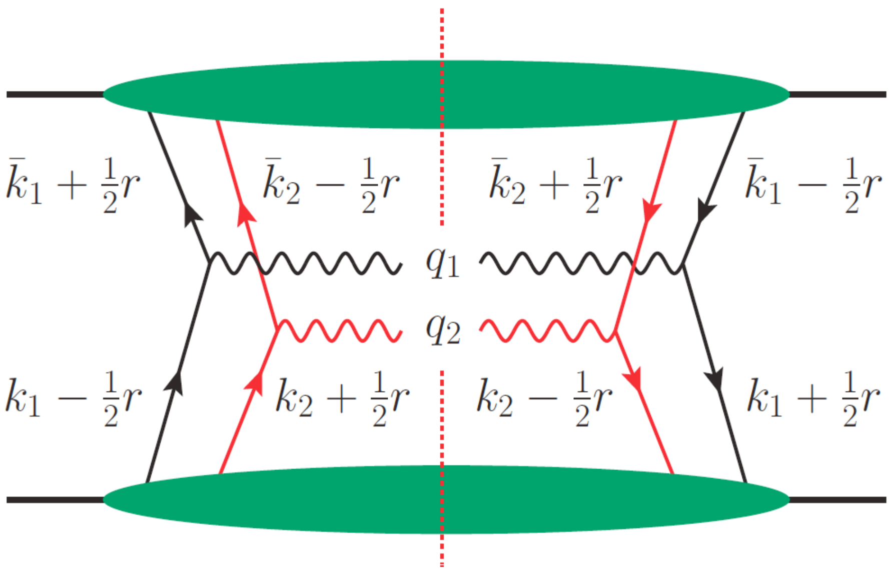

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- can extend $\hat{\sigma}_i$ to higher orders in α_s
  get usual convolution integrals over x_i in $\hat{\sigma}_i$ and F
- Fourier transform: $F(x_1, x_2, \boldsymbol{b}) \to F(x_1, x_2, \boldsymbol{r})$
  $\boldsymbol{r}$ = mismatch between parton momenta in scatt. amplitude
  and its conjugate

sometimes called "generalized parton distribution (GPD)"

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Double parton scattering: pocket formula

- if two-parton density factorizes as

$$F(x_1, x_2, \boldsymbol{b}) = f(x_1)\, f(x_2)\, G(\boldsymbol{b})$$

  where $f(x_i)$ = usual PDF

- if assume same $G(\boldsymbol{b})$ for all parton types
  then cross sect. formula turns into

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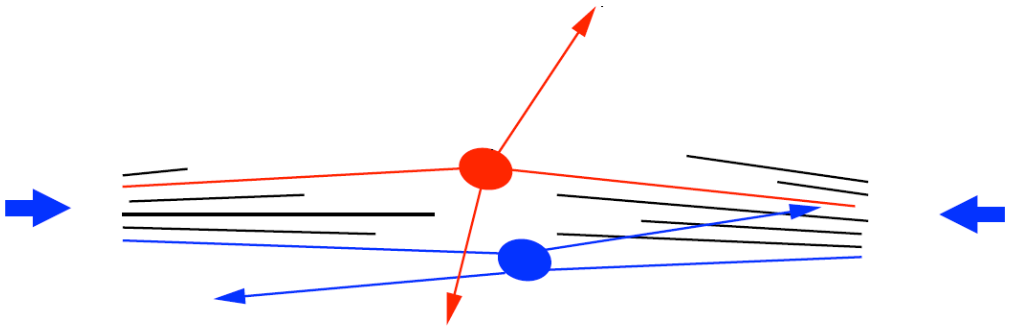
  with $\sigma_{\text{eff}} = 1 / \int d^2\boldsymbol{b}\, G^2(\boldsymbol{b})$

  $\rightsquigarrow$ scatters are completely independent

- also works for σ_i at higher orders in α_s
- requires independent event selection criteria for particles produced in scatters 1 and 2

Double parton scattering: pocket formula



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  $\rightsquigarrow$ scatters are completely independent

- ansatz can be extended from 2 to n hard scatters
- underlies bulk of phenomol. estimates
- underlies implementation of MPI in PYTHIA, HERWIG++ and SHERPA (AMISIC++)
  together with model for non-perturbative region below some $p_{T\,\text{min}}$
  and for subsequent soft interactions $\rightsquigarrow$ "color reconnection"

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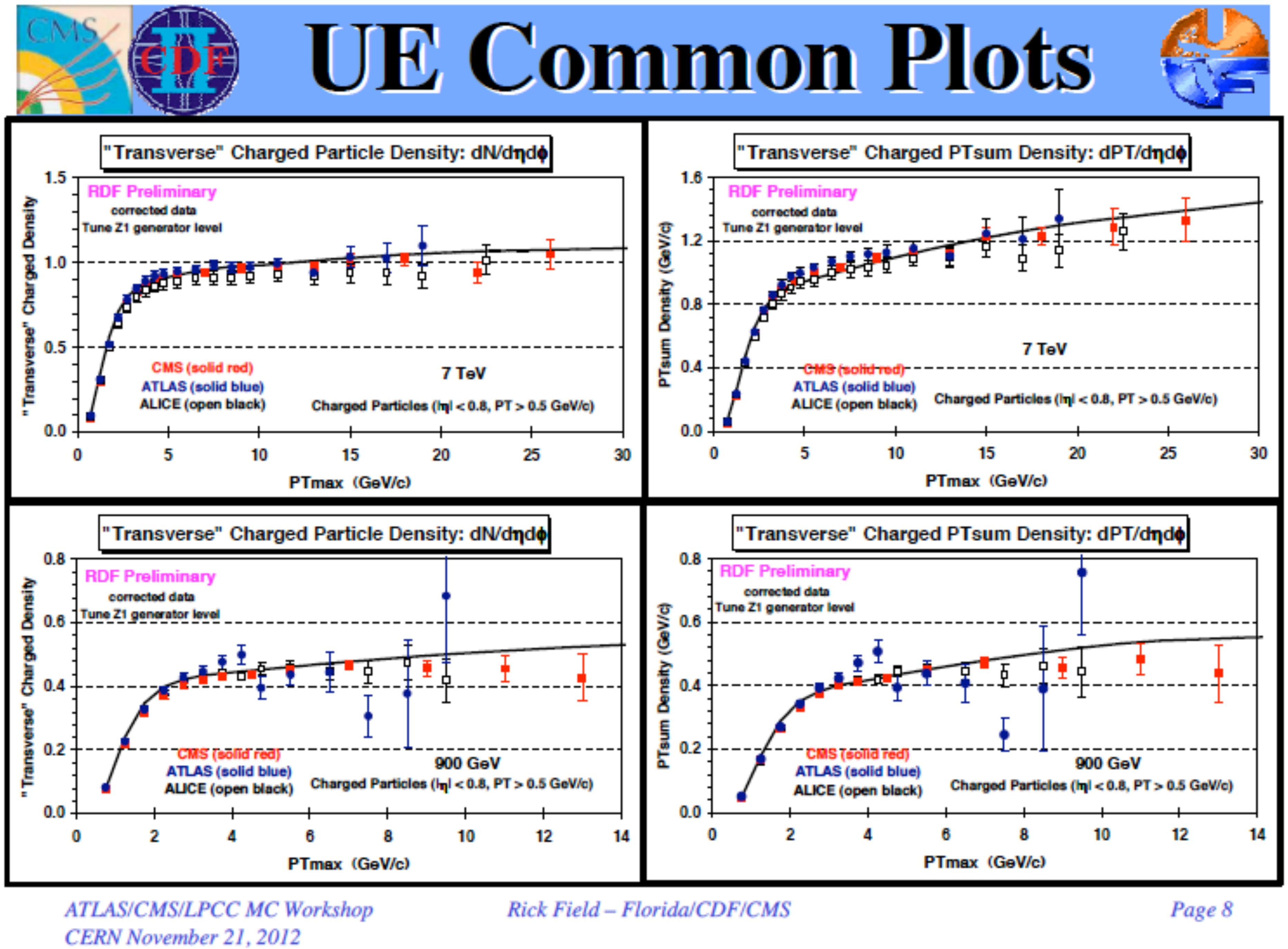
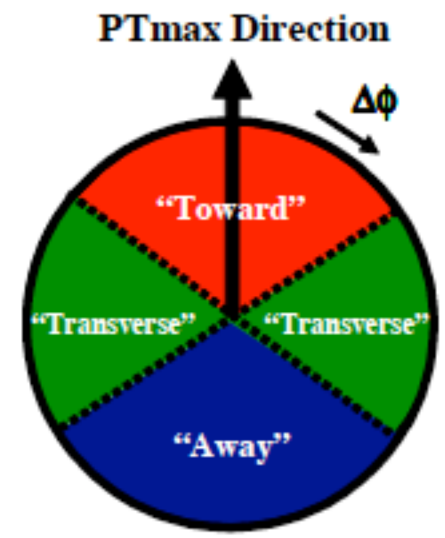
  $\rightsquigarrow$ scatters are completely independent

- relies on strong simplifications
  must expect that is only approximate
  $\rightsquigarrow$ suitable as guideline, but not when precision is needed

Underlying event studies at LHC

choose observables sensitive to soft particle production

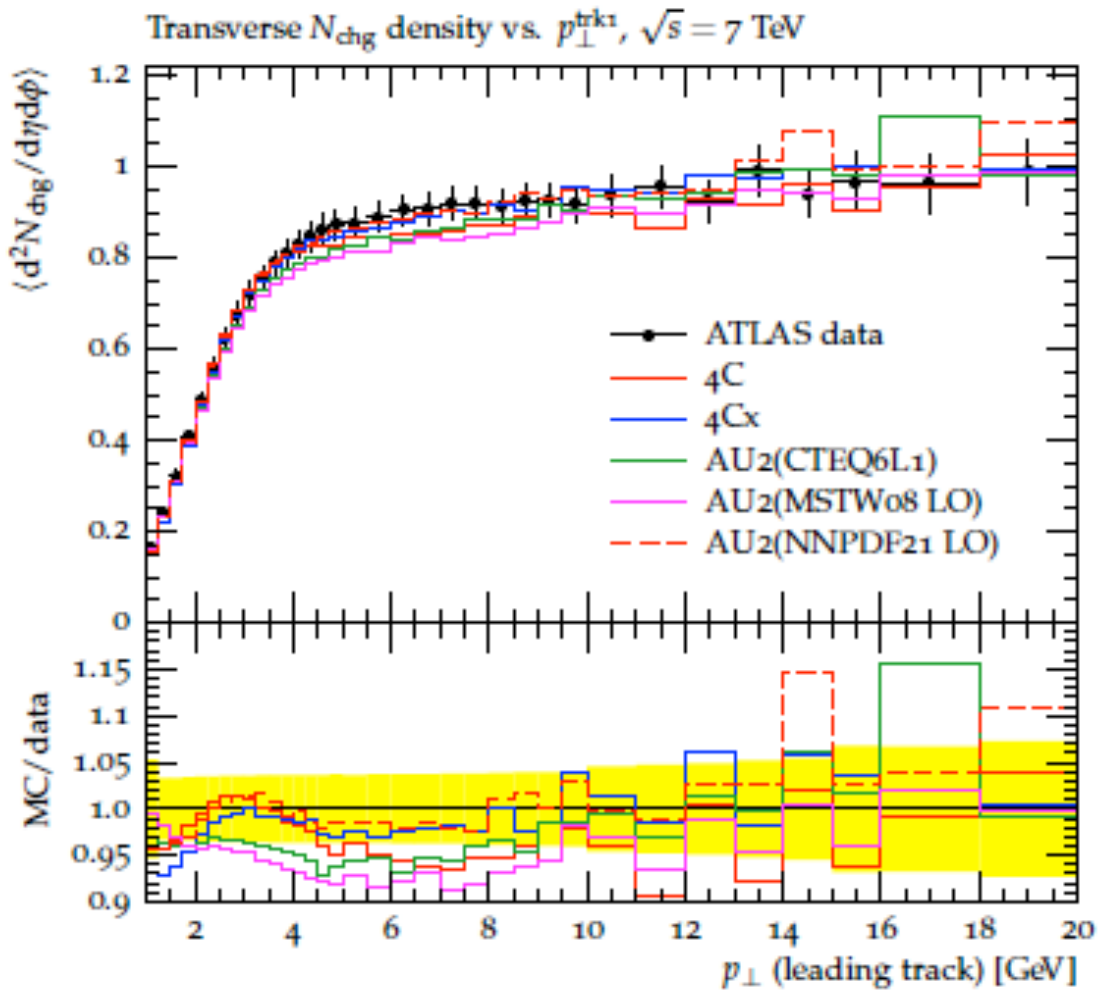


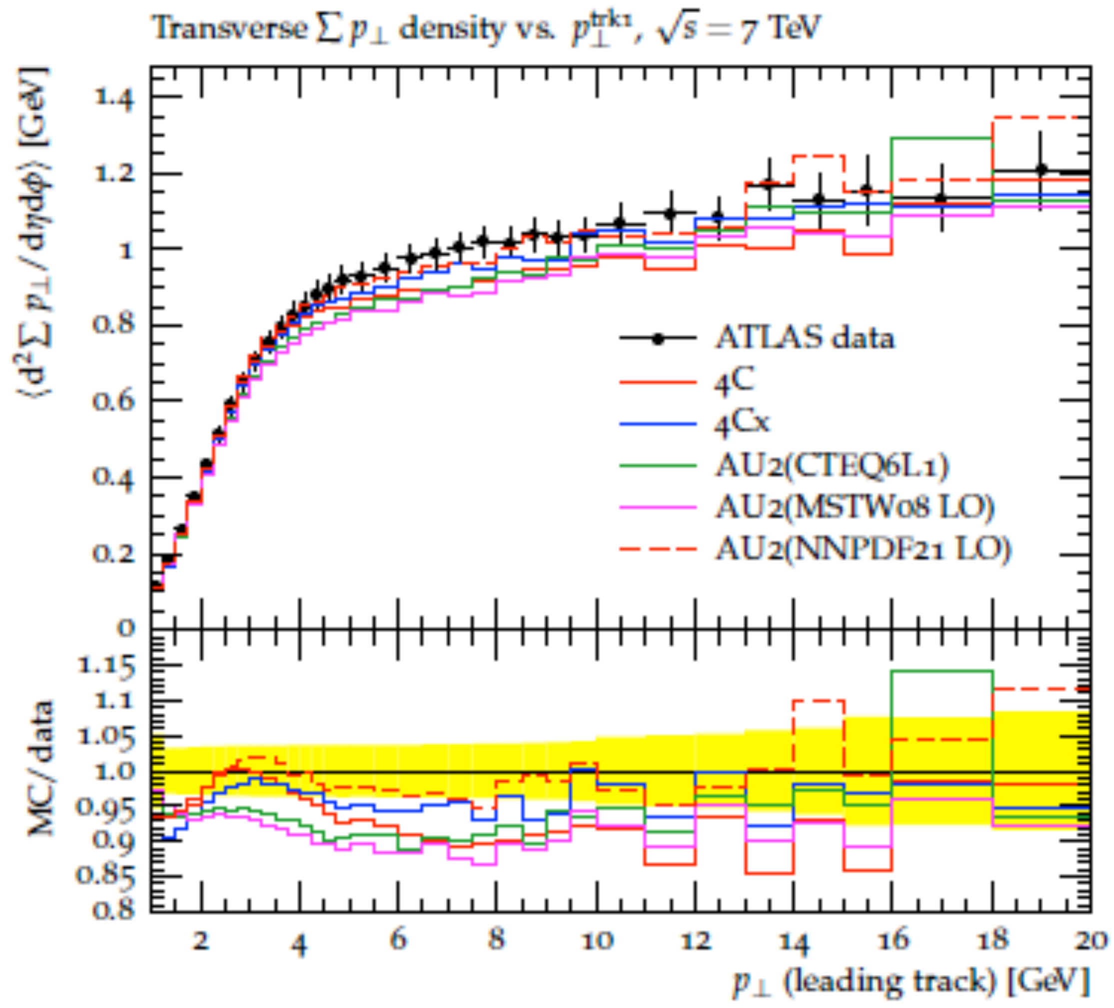


Plots: Rick Field

Underlying event studies at LHC

used for tuning of Monte Carlo parameters

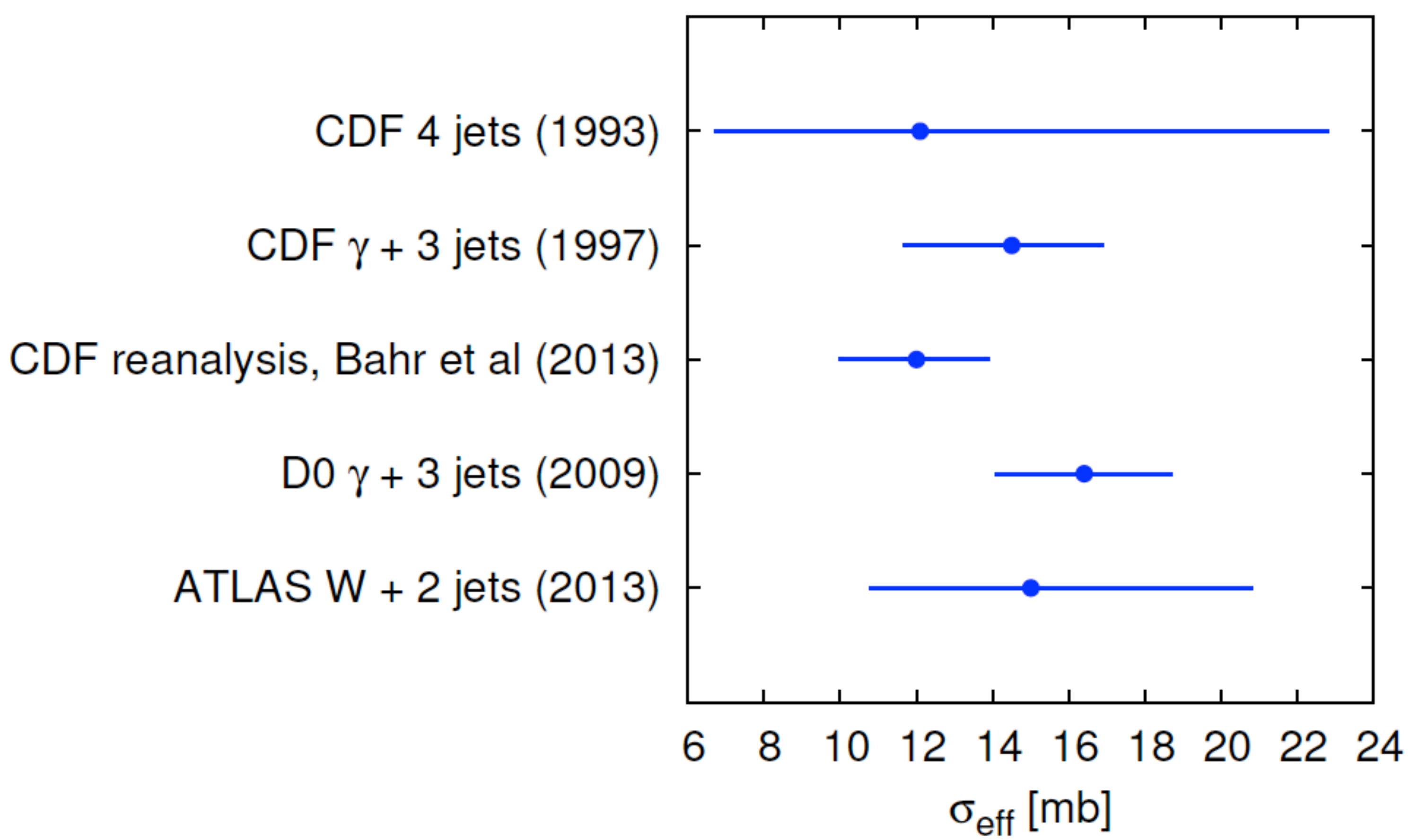


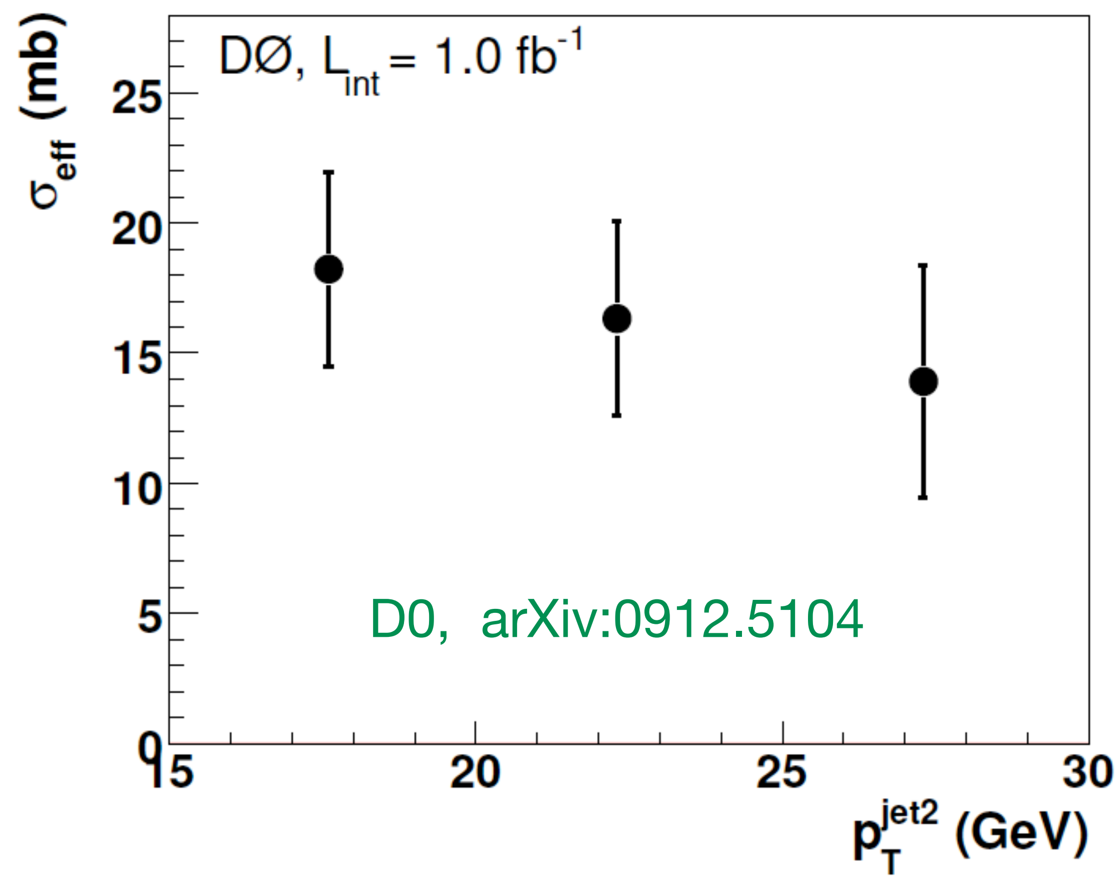


Plots: S. Wahrmund for the ATLAS Collaboration, MPI@LHC 2012

see parallel talks: D Kar (WG4, Tue 15:00), K Mazumdar (WG2, Tue 15:20), O Kepka (WG2, Thu 8:30)
apologies if here or in the following I have missed references to parallel sessions!

Determinations of σ_{eff} from double hard scattering

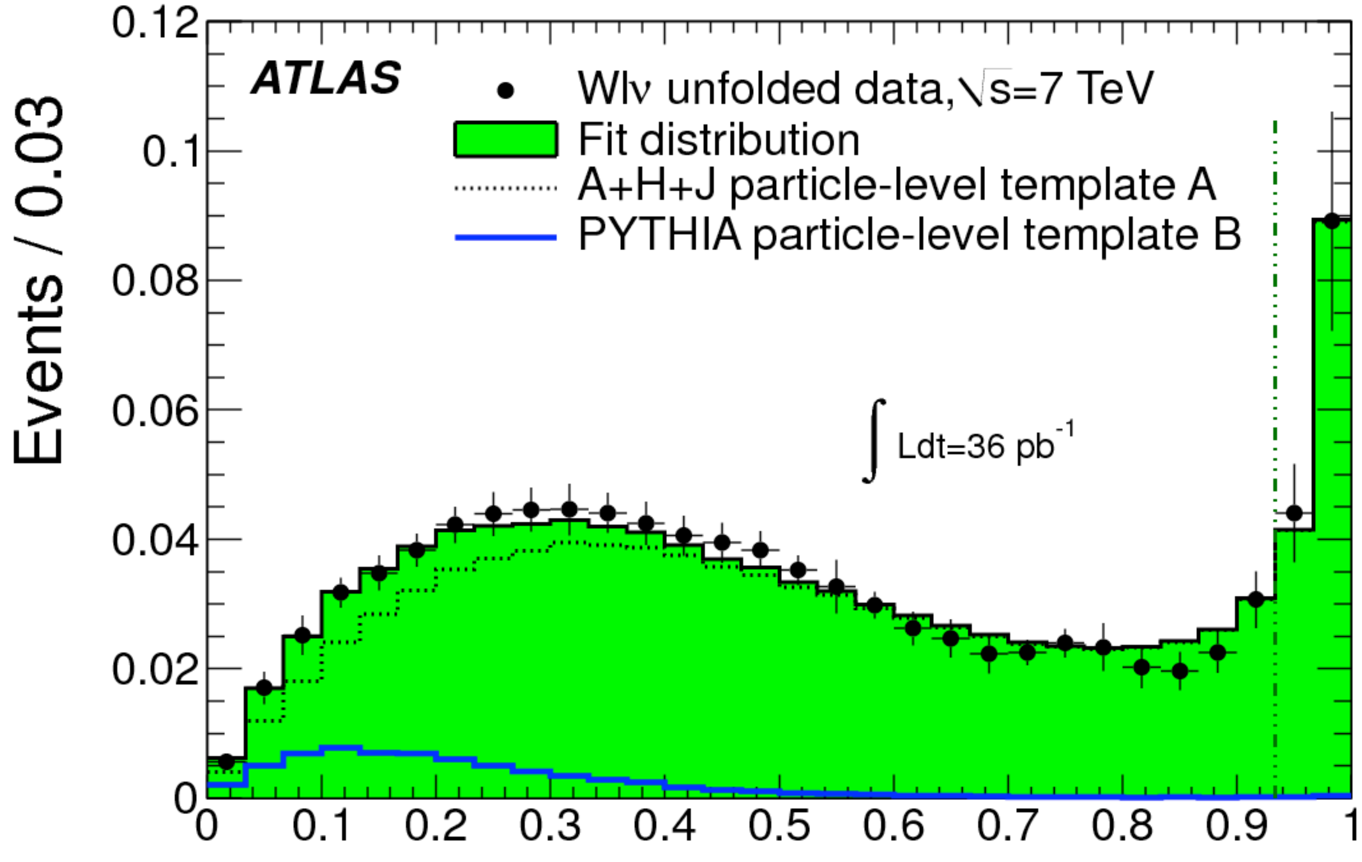




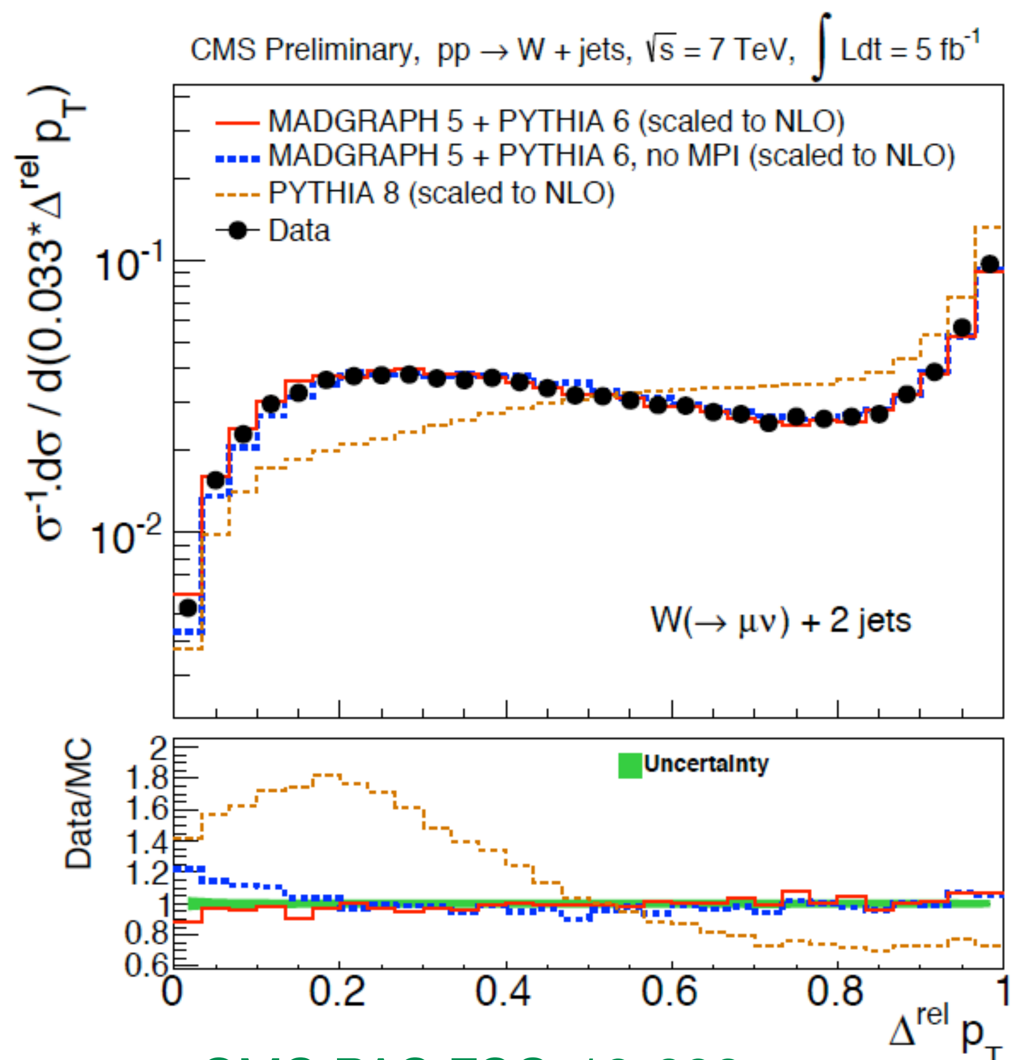
- all determinations in same ballpark for σ_{eff}
- no clear variation with kinematics reported so far

Double parton scattering in pp→ W + 2 jets + X

W + exactly 2 jets with p_T > 20 GeV



ATLAS, arXiv:1301.6872



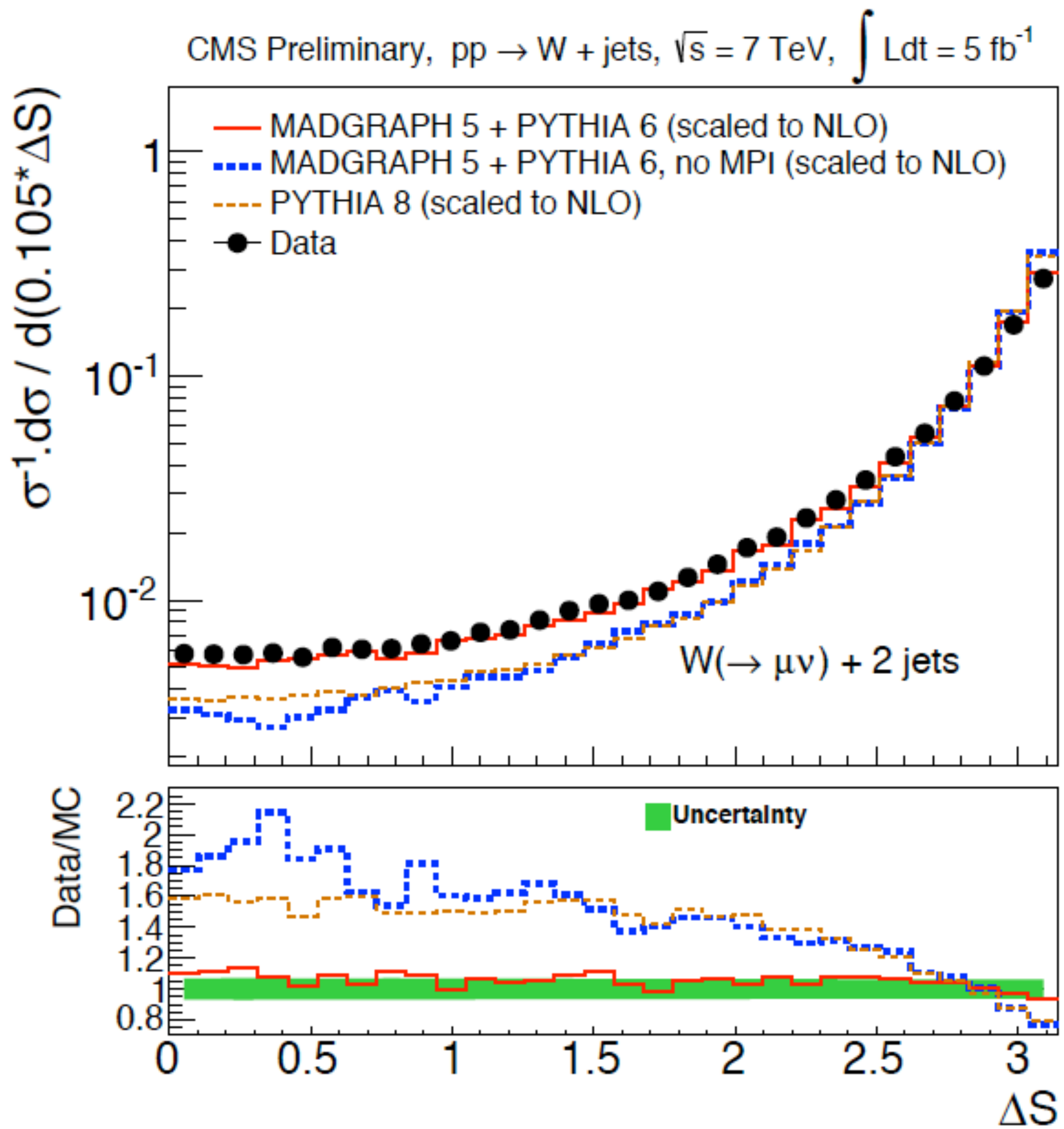
CMS PAS FSQ-12-028

- ATLAS fits distribution to two templates
  - ★ A (single hard scatt.) and B (double hard scatt.)
  - ★ extract double scattering fraction f_{DP} = 0.08 ± 0.01 ± 0.02

$$\Delta^n_{\text{jets}} = \Delta^{\text{rel}}\, p_T = \frac{|\boldsymbol{p}_{T\text{jet1}} + \boldsymbol{p}_{T\text{jet2}}|}{|\boldsymbol{p}_{T\text{jet1}}| + |\boldsymbol{p}_{T\text{jet2}}|}$$

see parallel talks: P Bartalini (CMS) and M Myska (ATLAS), WG2, Tue 17:10 and 17:30

Double parton scattering in pp→ W + 2 jets + X



$$\Delta S = \angle(\boldsymbol{p}_{T,W},\ \boldsymbol{p}_{T\text{jet1}} + \boldsymbol{p}_{T\text{jet2}})$$

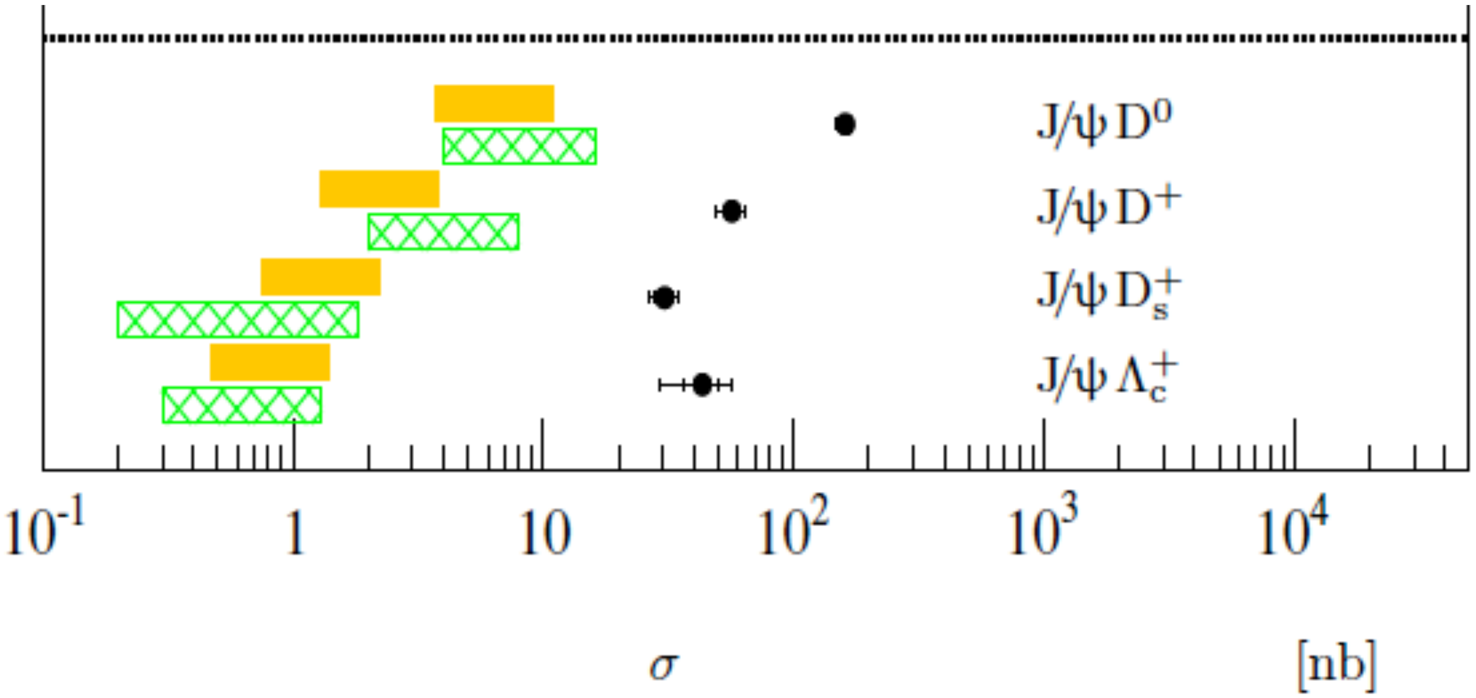
for single hard scattering peaked at π

for double hard scattering flat if two scatters are completely independent

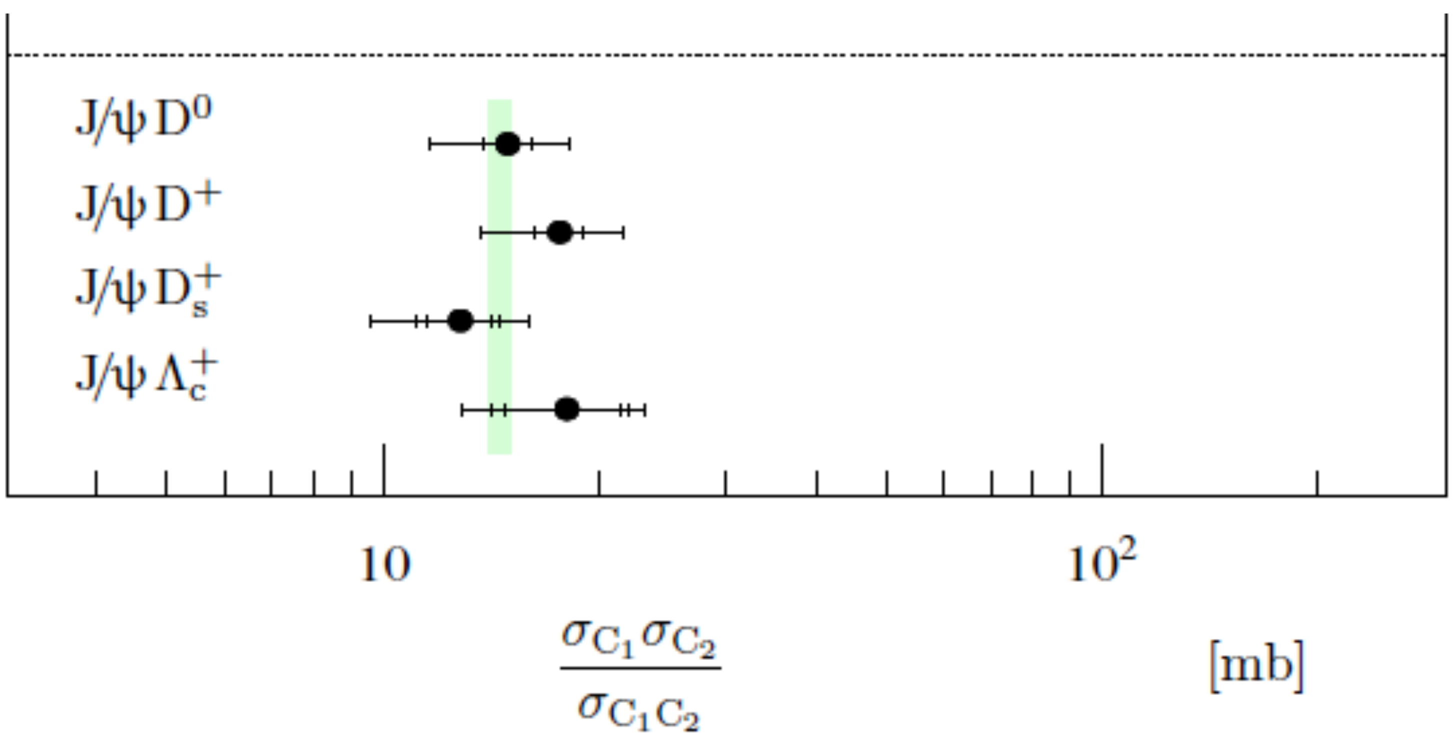
but need not be flat if have correlations between two partons in proton (see later)

special thanks to S Bansal, P Bartalini and H Jung for discussions

LHCb: double charm production ($c\bar{c}c\bar{c}$)



J/Ψ + D channels: σ much larger than computed for single hard scatt.



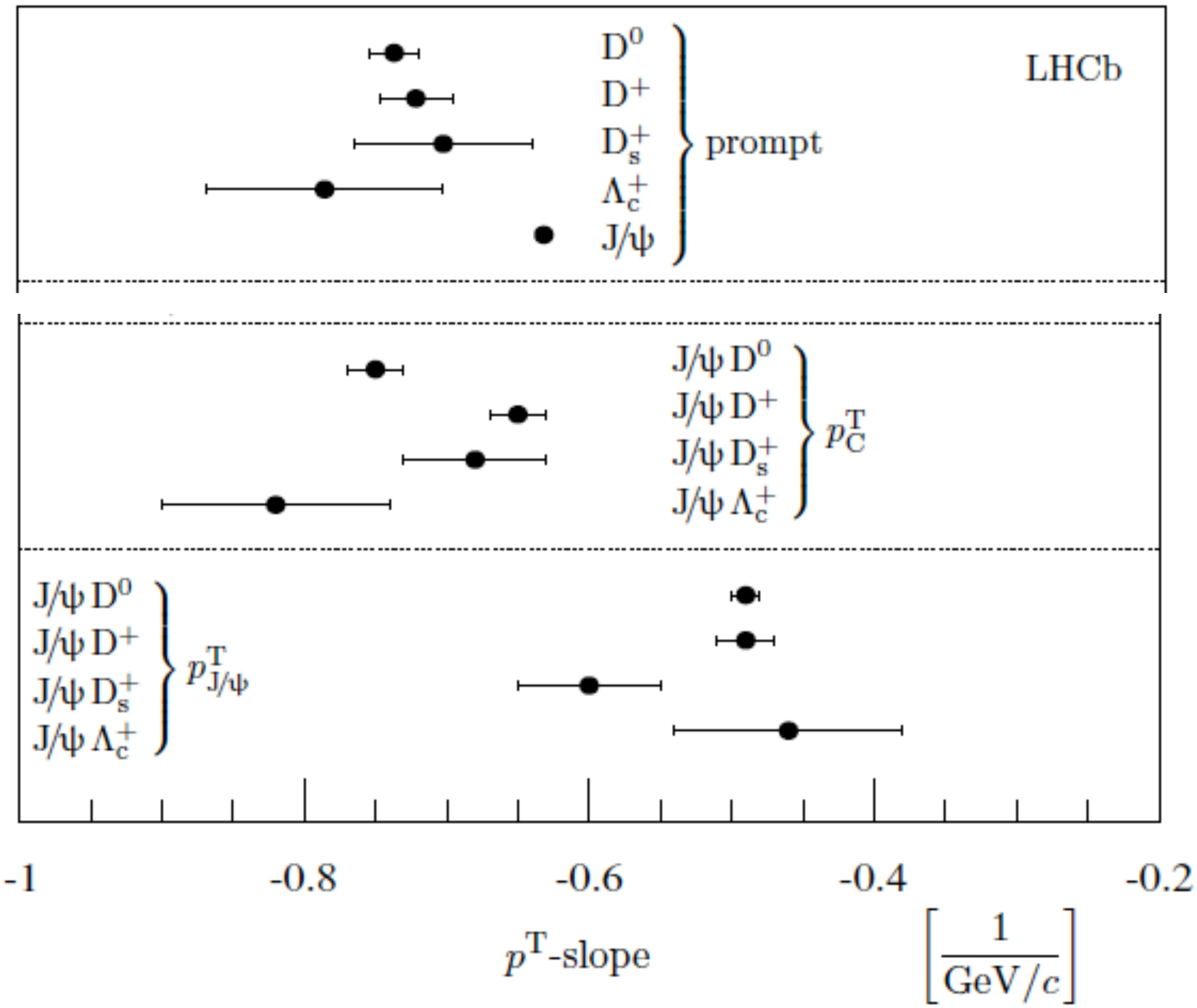
size of cross sect. ratio in ballpark of σ_{eff} from other processes

double J/Ψ production: similar size estimated for single and double scattering

LHCb, arXiv:1109.0963
and several theory papers

Plots: LHCb, arXiv:1205.0975

LHCb: double charm production ($c\bar{c}c\bar{c}$)



p slopes similar in single and double scattering channels for J/Ψ but not for D mesons

not consistent with assumption of completely independent scatters

situation currently not clear

Plot: LHCb, arXiv:1205.0975

see parallel talks (theory): N Zotov and R Maciula, WG4/5, Wed 15:00 and 15:20

Parton correlations

parallel talk: MD (WG2, Tue 16:50)

recent work: Rogers, Strikman 2008; Domdey et al 2011; Flensburg et al 2011

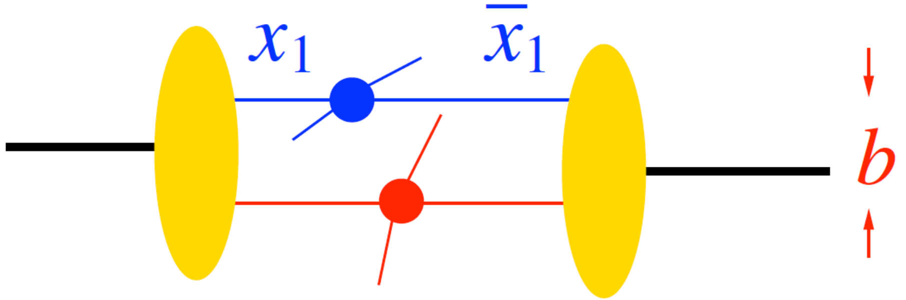
pocket formula $\sigma_{\text{double}} = (\sigma_1 \sigma_2)/(C\sigma_{\text{eff}})$ is invalid if have correlations between

- x_1 and x_2 of partons
  - most obvious: energy conservation $\Rightarrow \; x_1 + x_2 \le 1$
    often used: $F(x_1, x_2, \boldsymbol{b}) = f(x_1)\, f(x_2)\, (1 - x_1 - x_2)^n\, G(\boldsymbol{b})$
  - significant $x_1 - x_2$ correlations found in constituent quark model
    Rinaldi, Scopetta, Vento 2013
- x_i and $\boldsymbol{b}$
  even for single partons see correlations between x and $\boldsymbol{b}$ distribution
  - HERA results on $\gamma p \to J/\Psi\, p$ give
    $$\langle \boldsymbol{b}^2 \rangle \propto \text{const} + 4\alpha' \log(1/x) \quad \text{with} \quad \alpha' \approx (0.08\,\text{fm})^2$$
    for gluons with $x \sim 10^{-3}$
  - lattice simulations $\to$ strong decrease of $\langle \boldsymbol{b}^2 \rangle$ with x above ~ 0.1
  - precise mapping of single-parton distributions $f(x, \boldsymbol{b})$ over wide x range in future lepton-proton experiments
    JLab 12, COMPASS, EIC, LHeC
    $\to$ parallel talks in WG6 and WG7

  plausible to expect similar correlations in two-parton distributions

Consequence for multiple interactions

- indications for decrease of $\langle \boldsymbol{b}^2 \rangle$ with x
- if interaction 1 produces high-mass system
  $\rightarrow$ have large $x_1, \bar{x}_1$
  $\rightarrow$ smaller $\boldsymbol{b}$, more central collision
  $\rightarrow$ secondary interactions enhanced
  Frankfurt, Strikman, Weiss 2003
  study in Pythia: Corke, Sjöstrand 2011



σ_{tot} revisited

$F(x_1, x_2, b) = f(x_1)\, f(x_2)\, G(b)$

- exercise: assume absence of parton correlations
  and Gaussian $\boldsymbol{b}$ distribution of single parton with average $\langle \boldsymbol{b}^2 \rangle$

$$\Rightarrow \quad \sigma_{\text{eff}} = 4\pi \langle \boldsymbol{b}^2 \rangle = 41\,\text{mb}\, \frac{\langle \boldsymbol{b}^2 \rangle}{(0.57\,\text{fm})^2}$$

determinations of $\langle \boldsymbol{b}^2 \rangle$ range from $\sim (0.57\,\text{fm} - 0.67\,\text{fm})^2$

if $\boldsymbol{b}$ distrib. is Fourier trf. of dipole then get extra factor $7/8$ in σ_{eff}

is $\gg \sigma_{\text{eff}} \sim 10$ to $20\,\text{mb}$ from experimental extractions

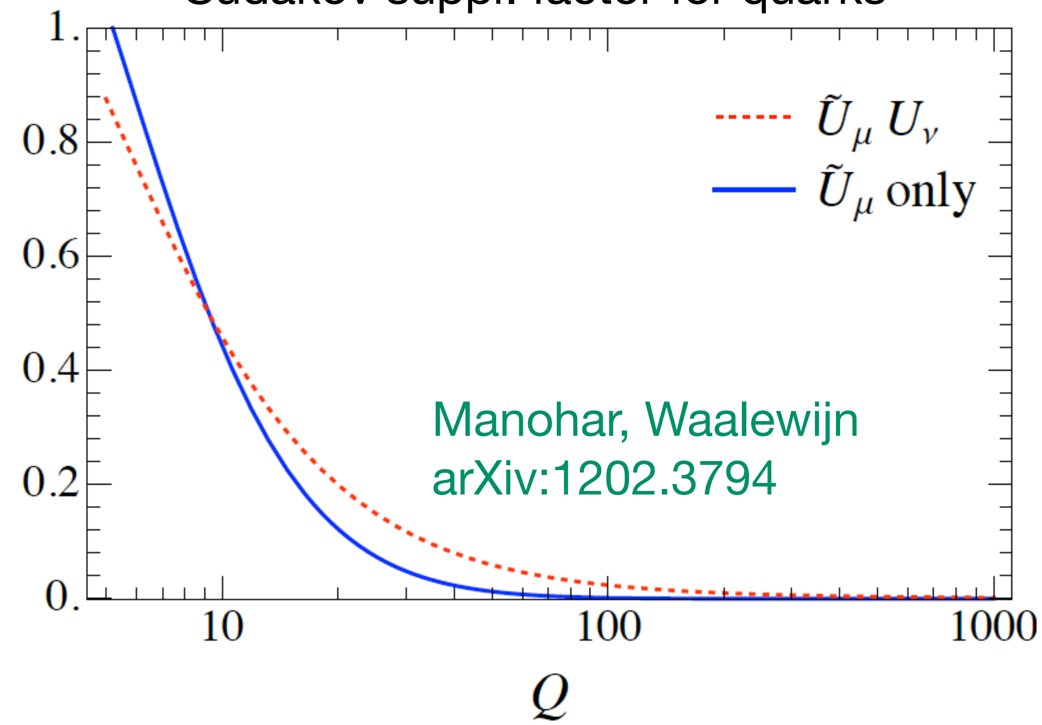
Parton spin correlations

- possible even in unpolarized proton
- detailed study for double Drell-Yan process (two gauge bosons)
  Kasemets, MD 2012
  - longitudinal pol. correlations $\to$ change σ_{double}
  - correlations between transverse quark
    $\to$ azimuthal correlations between lepton decay planes of two bosons
  - expect analogous effects with dijets instead of gauge bosons
- strong spin correlations found in MIT bag model
  Chang, Manohar, Waalewijn 2012
- unkown: how important are spin correlations at small x?

Color correlations

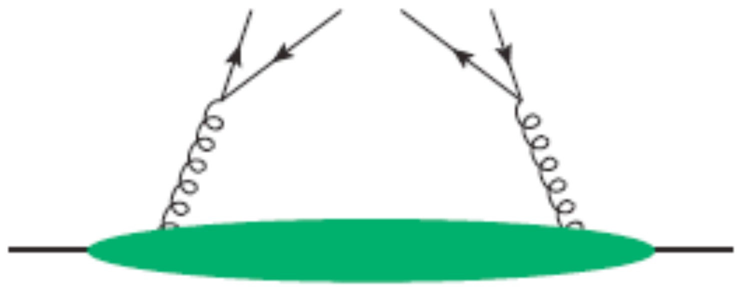
- correlations between color of two partons suppressed by Sudakov logarithms
  Mekhfi 1988; Manohar, Waalewijn 2012

Sudakov suppr. factor for quarks



Behavior at small interparton distance

- for $\boldsymbol{b} \ll 1/\Lambda$ in perturbative region $F(x_1, x_2, \boldsymbol{b})$ dominated by graphs with splitting of single parton



- find strong spin and color correlations between two partons

  e.g. 100% correlation for longitudinal pol. of q and $\bar{q}$

- can compute short-distance behavior:

$$F(x_1, x_2, \boldsymbol{b}) \sim \frac{1}{\boldsymbol{b}^2} \text{ splitting fct} \otimes \text{usual PDF}$$

Scale evolution

consider only distributions for partons without color correlation

- if define two-parton distributions as operator matrix elements in analogy with usual PDFs

$$F(x_1, x_2, \boldsymbol{b}; \mu) \sim \langle p | \mathcal{O}_1(\boldsymbol{0}; \mu)\, \mathcal{O}_2(\boldsymbol{b}; \mu) | p \rangle \qquad f(x; \mu) \sim \langle p | \mathcal{O}(\boldsymbol{0}; \mu) | p \rangle$$

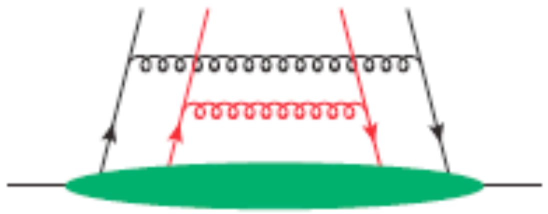
  where $\mathcal{O}(\boldsymbol{b}; \mu)$ = twist-two operator renormalized at scale μ

- $F(x_i, \boldsymbol{b})$ for $\boldsymbol{b} \neq \boldsymbol{0}$:

  separate DGLAP evolution for partons 1 and 2

$$\frac{d}{d \log \mu} F(x_i, \boldsymbol{b}) = P \otimes_{x_1} F + P \otimes_{x_2} F$$

  two independent parton cascades



- $\int d^2\boldsymbol{b}\, F(x_i, \boldsymbol{b})$:

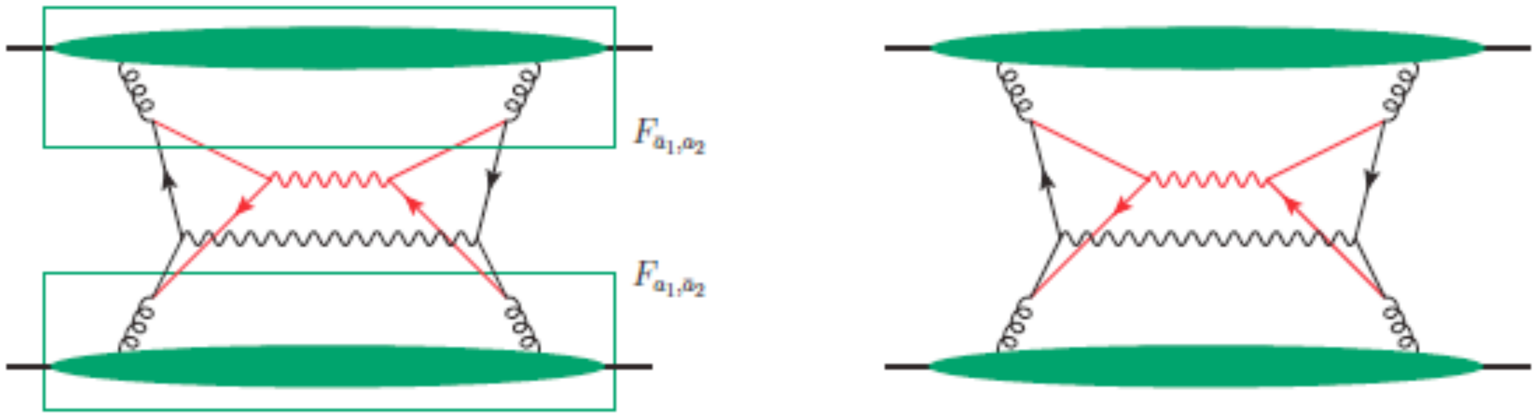
  extra term from $2 \to 4$ parton transition

  since $F(x_i, \boldsymbol{b}) \sim 1/\boldsymbol{b}^2$

  Kirschner 1979; Shelest, Snigirev, Zinovev 1982
  Gaunt, Stirling 2009; Ceccopieri 2011

- which evolution eq. is relevant for double hard scattering?

Deeper problems with the splitting graphs



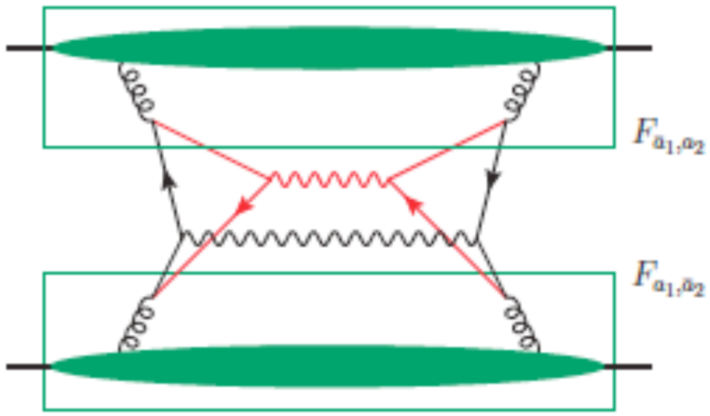
- contribution from splitting graphs in cross section gives divergent integrals $\int d^2\boldsymbol{b}\, F(x_1, x_2, \boldsymbol{b})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{b}) \sim \int d\boldsymbol{b}^2/\boldsymbol{b}^4$
- double counting problem between double scattering with splitting and single scattering at loop level

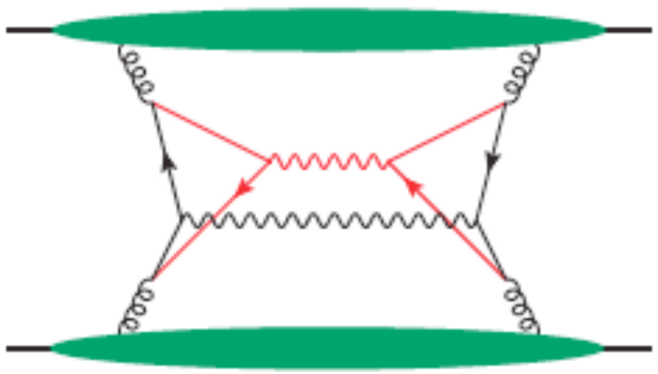
MD, Ostermeier, Schäfer 2011; Gaunt, Stirling 2011; Gaunt 2012
Blok, Dokshitzer, Frankfurt, Strikman 2011; Ryskin, Snigirev 2011, 2012
same problem for jets: Cacciari, Salam, Sapeta 2009

- possible solution:
  subtract splitting contribution from two-parton dist's when $\boldsymbol{b}$ is small
  will also modify their scale evolution; remains to be worked out

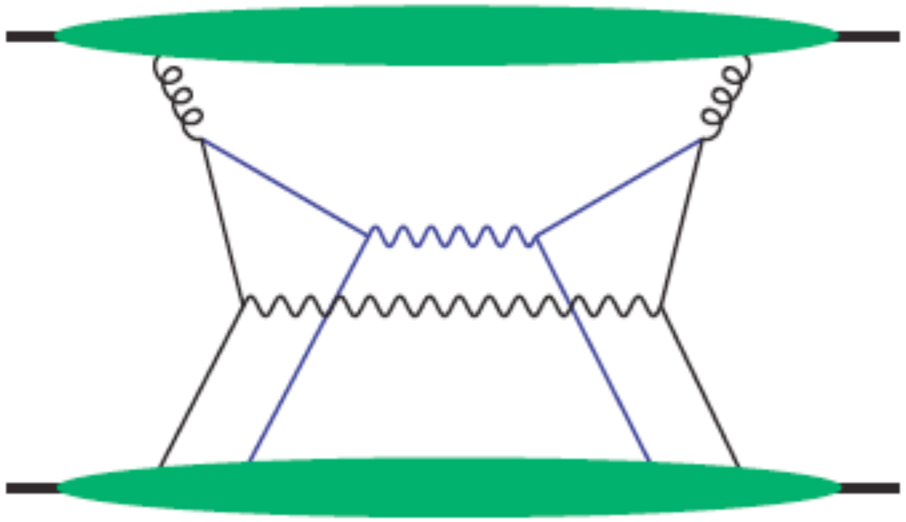
What is double parton scattering?

Deeper problems with the splitting graphs





- contribution from splitting graphs in cross section gives divergent integrals $\int d^2\boldsymbol{b}\, F(x_1, x_2, \boldsymbol{b})\, F(\bar{x}_1, \bar{x}_2, \boldsymbol{b}) \sim \int d\boldsymbol{b}^2/\boldsymbol{b}^4$
- double counting problem between double scattering with splitting



also have graphs with
single PDF for one proton
and double PDFs for other

Blok, Dokshitzer, Frankfurt, Strikman 2011

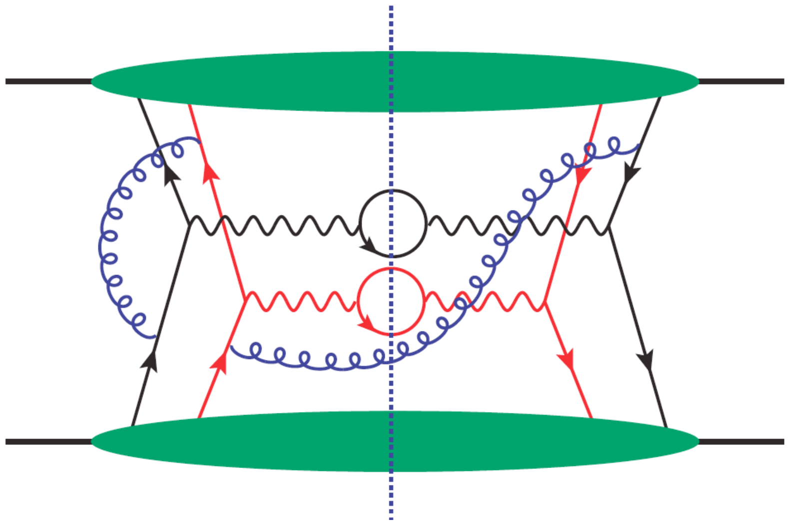
What is double parton scattering?

Towards a factorization proof for double scattering?

- simplest case: double Drell-Yan

processes with colored final states much more difficult

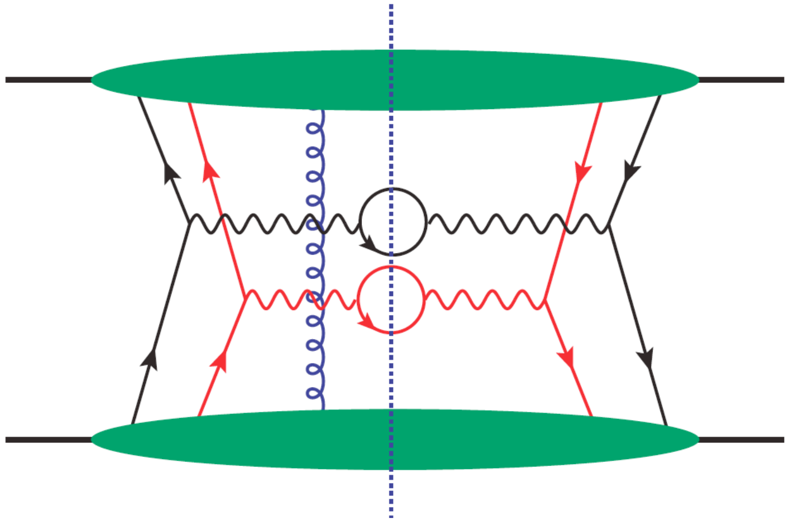
- open problem in ultraviolet region: parton splitting
- in infrared region: soft gluon exchange between scatters 1 and 2



★ partially under control
relevant to Sudakov factors
→ parton showers

MD, Ostermeier, Schäfer 2011

- open problem: soft gluon exchange in Glauber region



Topics not discussed in this talk

- phenomenological studies for many pp processes

double dijets: Domdey, Pirner, Wiedemann 2009; Berger, Jackson, Shaughnessy 2009
W/Z + jets: Maina 2009, 2011
like sign W pairs: Kulesza, Stirling 2009; Gaunt et al 2011; Berger et al 2011
double Drell-Yan: Kom, Kulesza, Stirling 2011
double charmonium: Kom, Kulesza, Stirling 2011; Baranov et al. 2011, 2012; Novoselov 2011
double charm: Berezhnoy et al 2012; Łuszczak et al 2011; Maciula, Szczurek 2012, 2013

- pA collisions

extra layer of compexity: two partons from same or from different nuclei in nucleus
Calucci, Treleani 2009, 2012; Strikman, Vogelsang 2009; Blok, Strikman, Wiedemann 2011; d'Enterria, Snigirev 2012, 2013

- small x approach — Flensburg et al 2011; Bartels, Ryskin 2011

- 'ridge effect' in pp and pA collisions

CMS; ATLAS; ALICE; many theory papers

only list references after 2008

Summary

- multiparton interactions are ubiquitous
  in hadron-hadron collisions

- populate characteristic part of phase space
  there they can be substantial part of rate

- important theory progress for hard double scattering

- but many open questions:

  ★ size of correlations between partons

  ★ parton splitting contributions ↔ evolution of DPDs

- promising experimental developments:

  ★ different processes

  ★ kinematic distributions

- use σ_{eff} as a handy tool, not as a precision instrument
  (if I have one free wish)