Standard Model (backgrounds) at the LHC

(part 3)

Prospects in Theoretical Physics 2013

Institute for Advanced Study, Princeton

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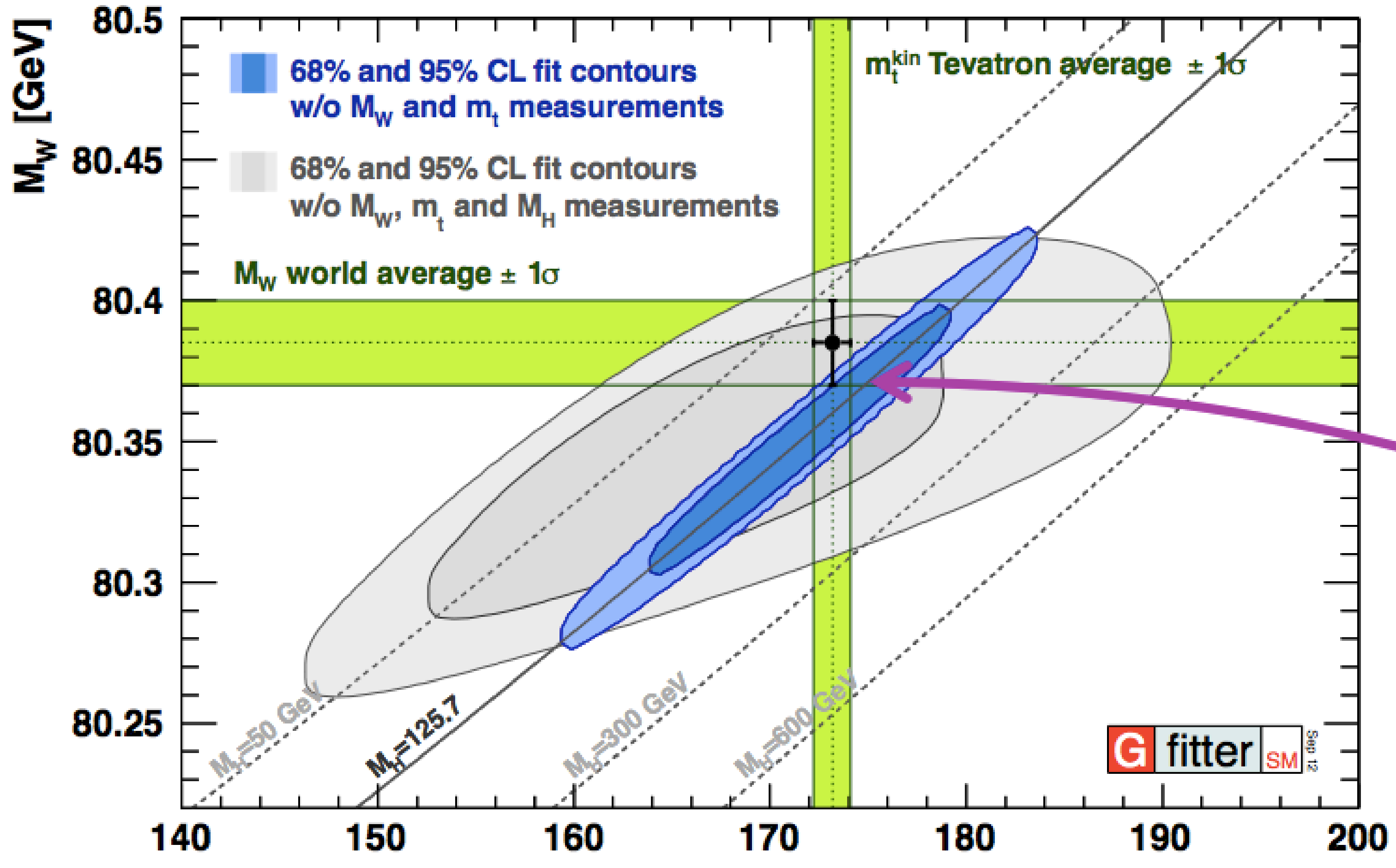
Top quark mass

Top quark mass



Baak et al, arXiv:1209.2716

Direct measurements (Tevatron averages):

m_{top}= 173.20±0.87 GeV
m_W = 80385±15 MeV

New EW fit results for m_{top} (m_W), including m_H, excluding the direct measurement of m_W (m_{top}) :

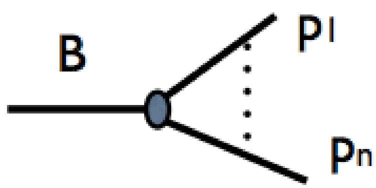
m_{top} = $175.8^{+2.7}_{-2.4}$ GeV
m_W = 80359 ± 11 MeV

Inclusion of m_H in EW fits greatly tightens correlation between m_W and m_{top}
introducing perhaps a slight tension ?

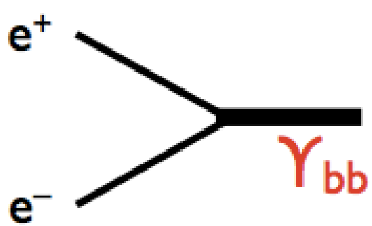
Continued improvement in the direct determination of m_W and m_{top} remains a high priority

Measuring the mass of heavy quarks: b/c

1. measure mass of B-hadrons or Υ_{bb}



$$m_B^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

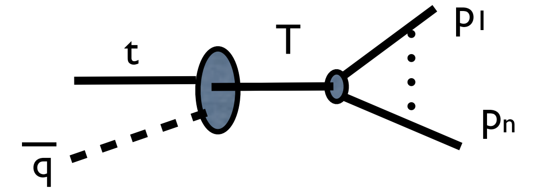


$$m_\Upsilon = \sqrt{S_{e^+e^-}}$$

2. $m_b = F_{\text{lattice/potential models}} (m_B, m_\Upsilon, \alpha_{QCD})$

Determination of m_{top} in hadronic collisions

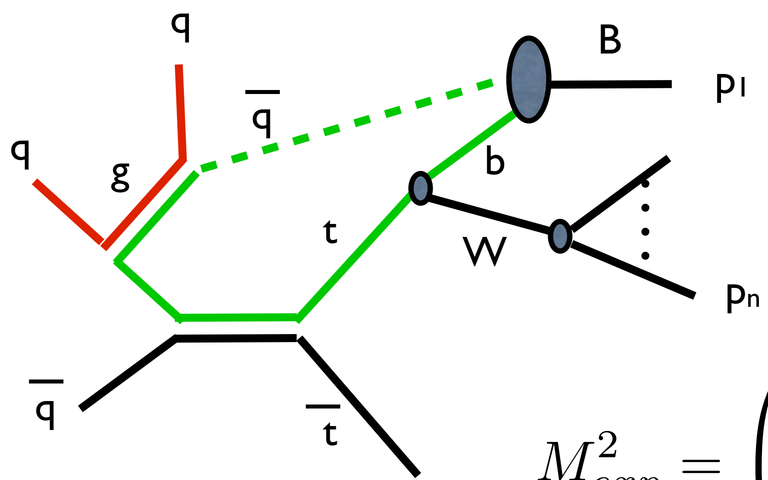
If Γ_{top} were < 1 GeV, top would hadronize before decaying. Same as b-quark



$$m_T^2 = \left(\sum_{i=1,\dots,n} p_i \right)^2$$

$m_t = F_{\text{lattice/potential models}} (m_T, \alpha_{QCD})$

But Γ_{top} is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured



$$M_{exp}^2 = \left(\sum_{i=1,\dots,n} p_i \right)^2$$

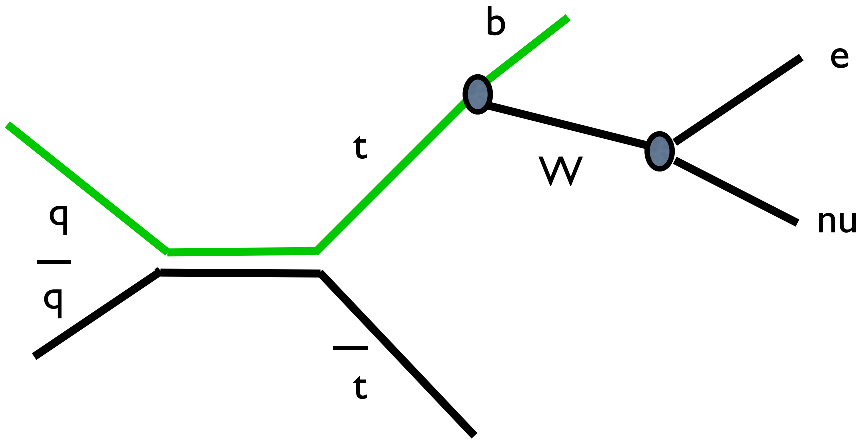
As a result, M_{exp} is not equal to m^{pole}_{top}, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{top}) \sim 1$ GeV

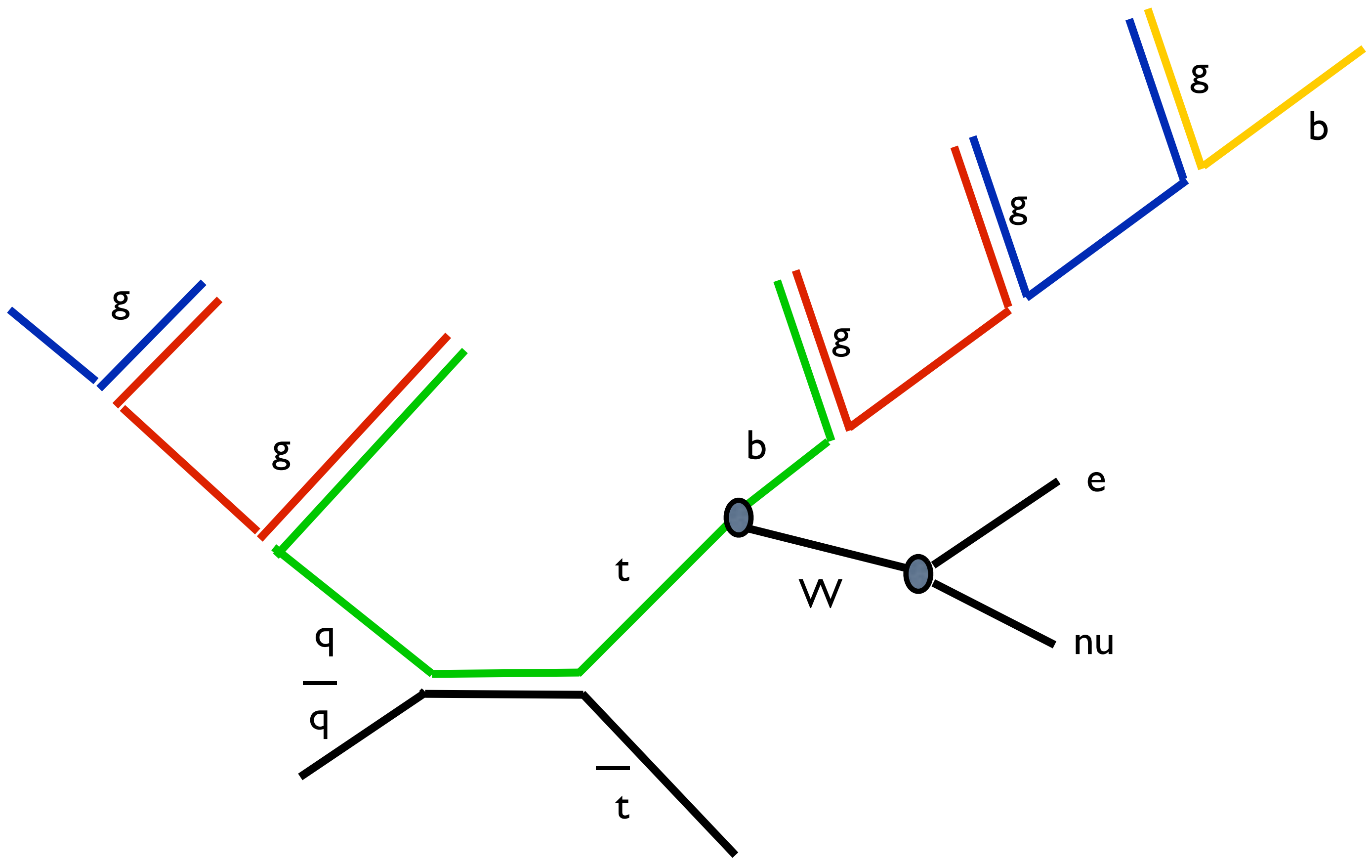
Goal:

- correctly quantify the systematic uncertainty
- identify observables that allow to validate the theoretical modeling of hadronization in top decays
- identify observables less sensitive to these effects

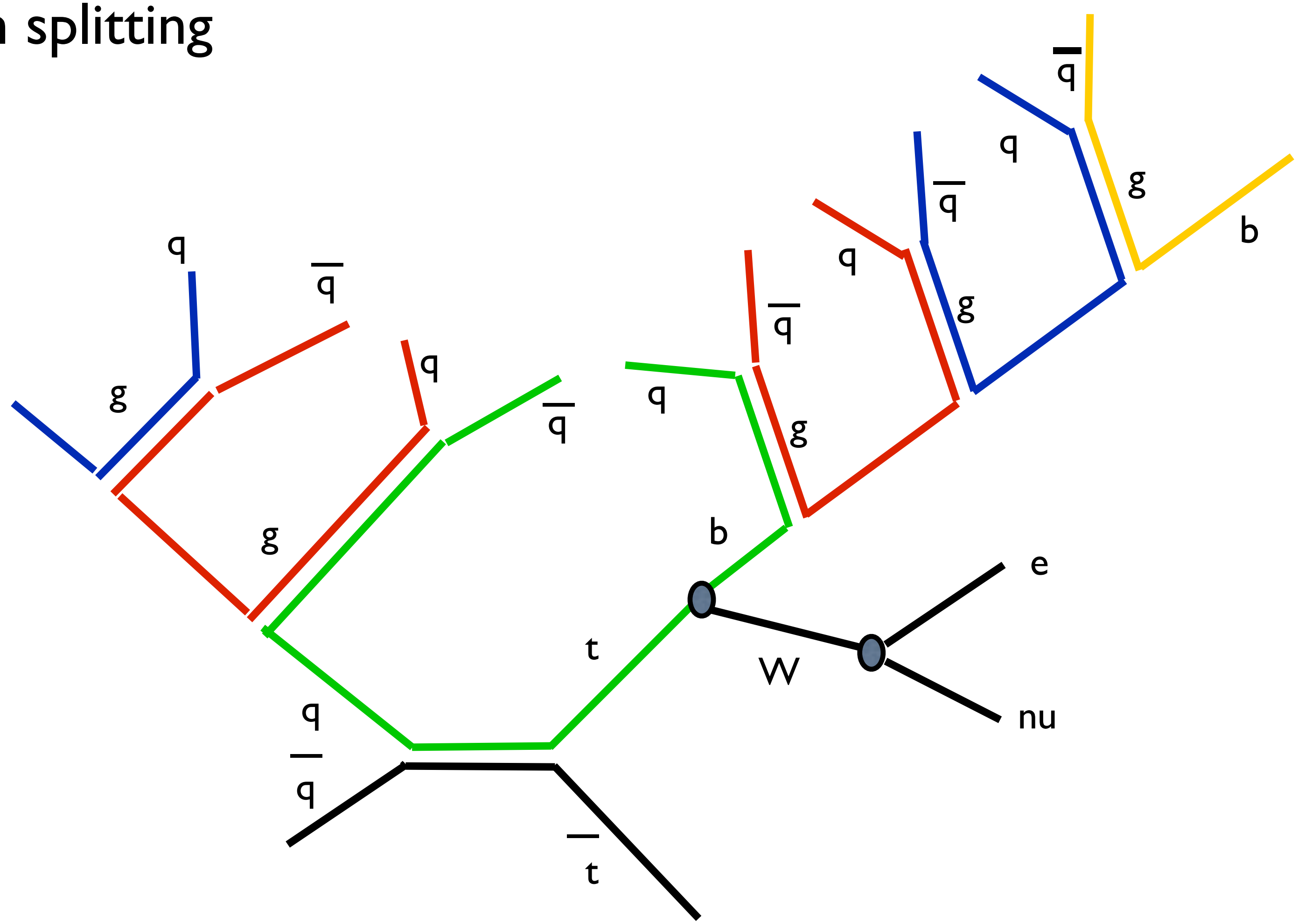
1. Hard Process



1. Hard Process
2. Shower evolution



1. Hard Process
2. Shower evolution
3. Gluon splitting



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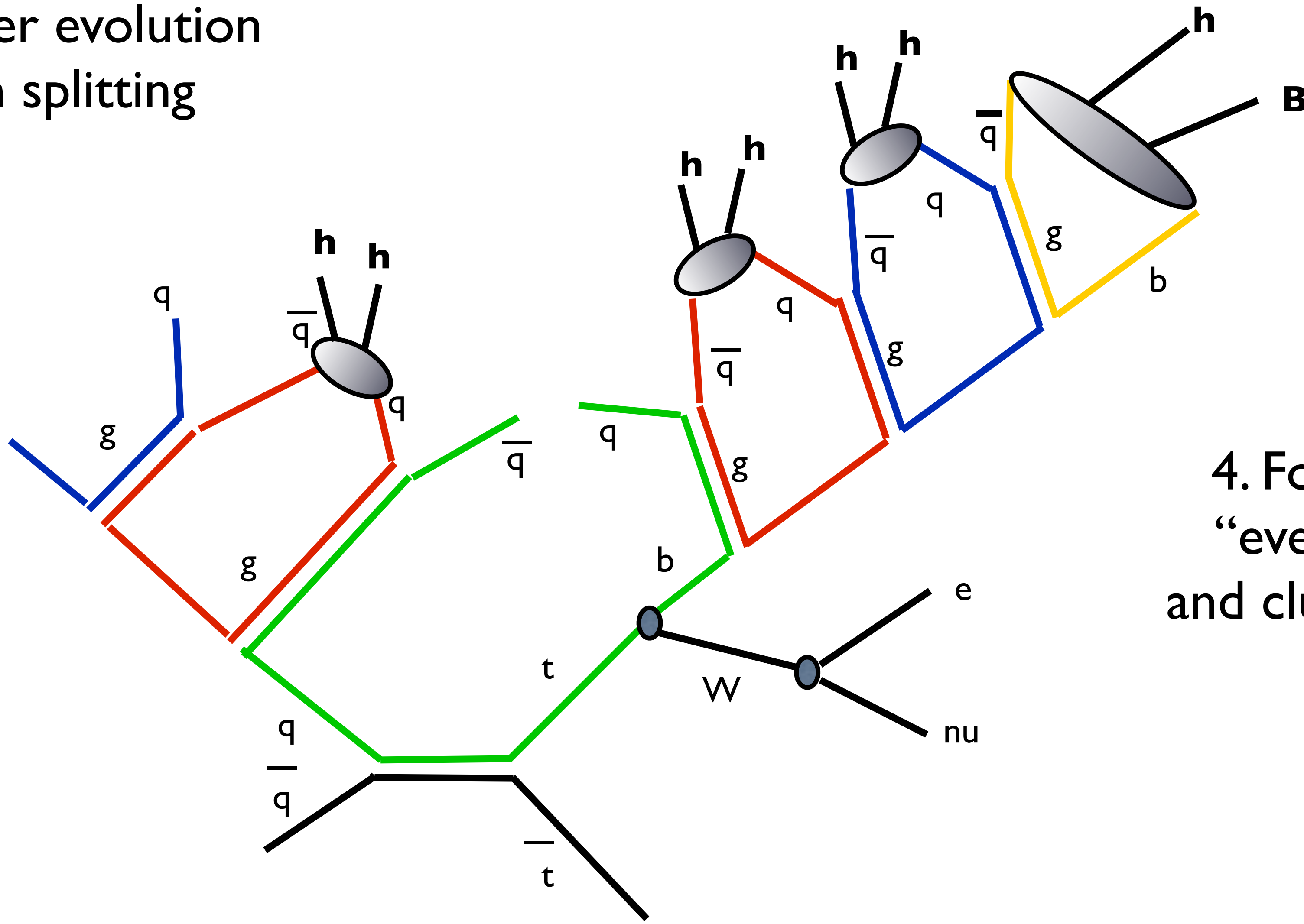
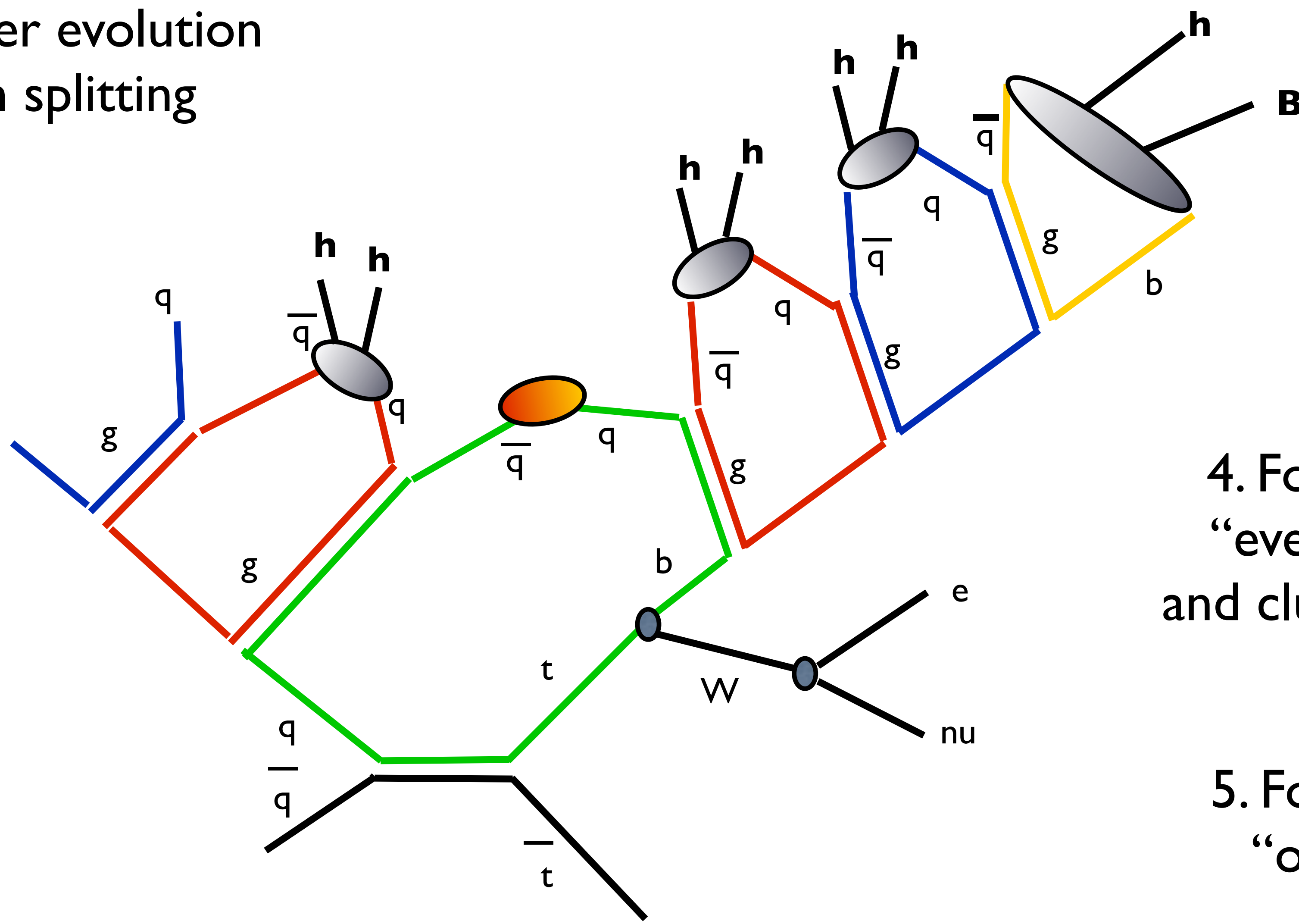


4. Formation of "even" clusters and cluster decay to hadrons

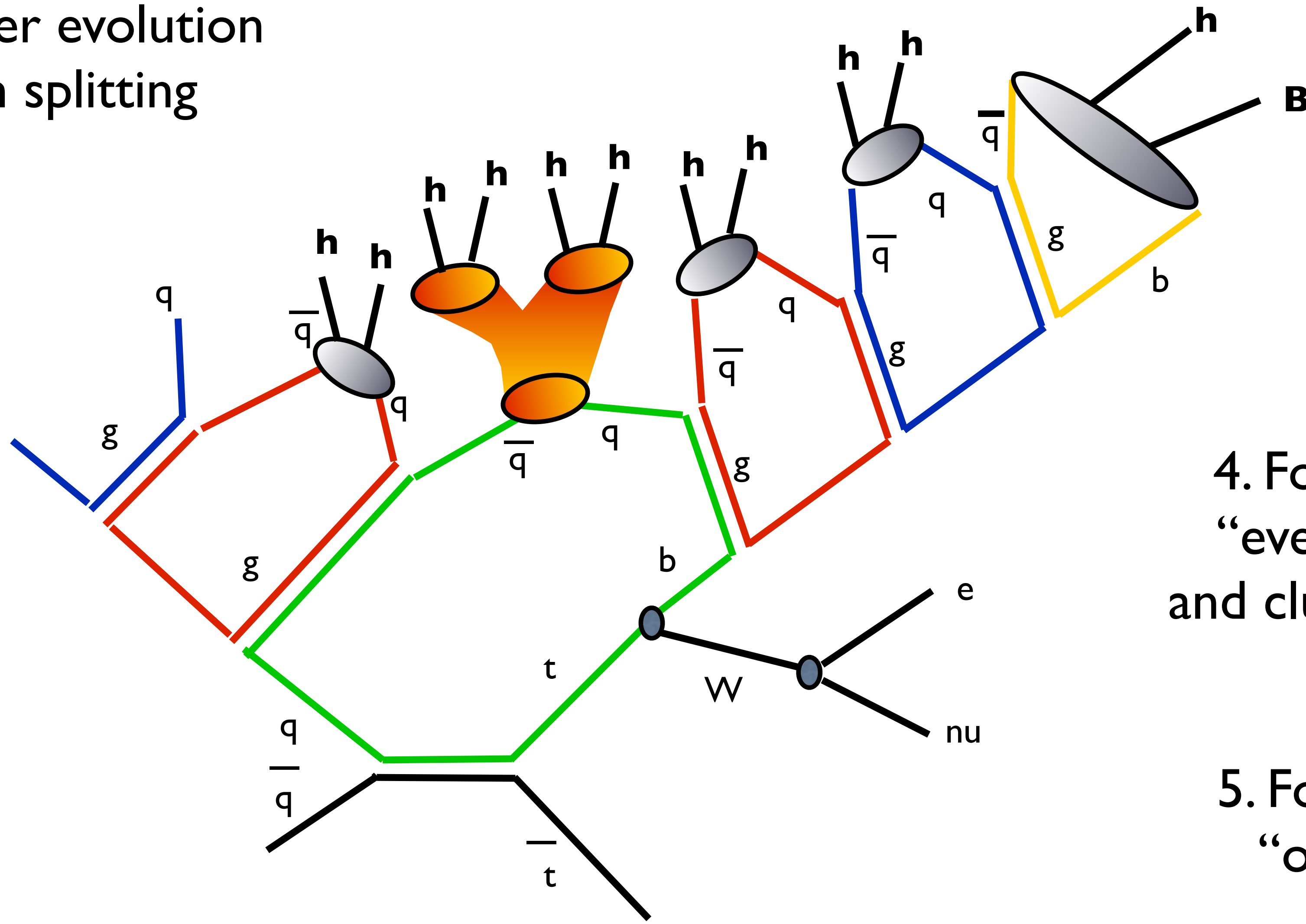
1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of
"even" clusters
and cluster decay
to hadrons

5. Formation of
"odd" cluster

1. Hard Process
2. Shower evolution
3. Gluon splitting

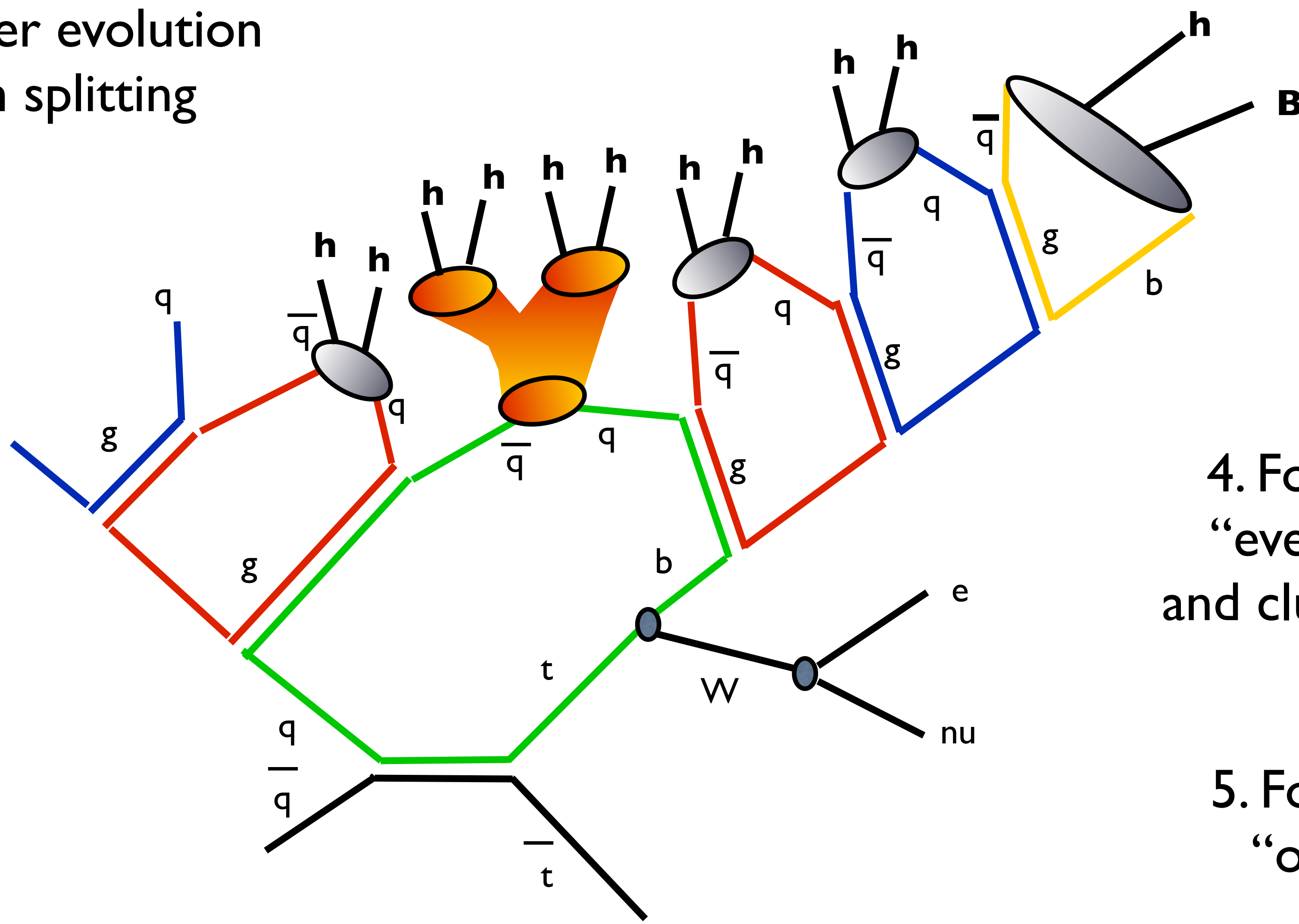


4. Formation of "even" clusters and cluster decay to hadrons

5. Formation of "odd" cluster

6. Decay of "odd" clusters, if large cluster mass, and decays to hadrons

1. Hard Process
2. Shower evolution
3. Gluon splitting



4. Formation of "even" clusters and cluster decay to hadrons

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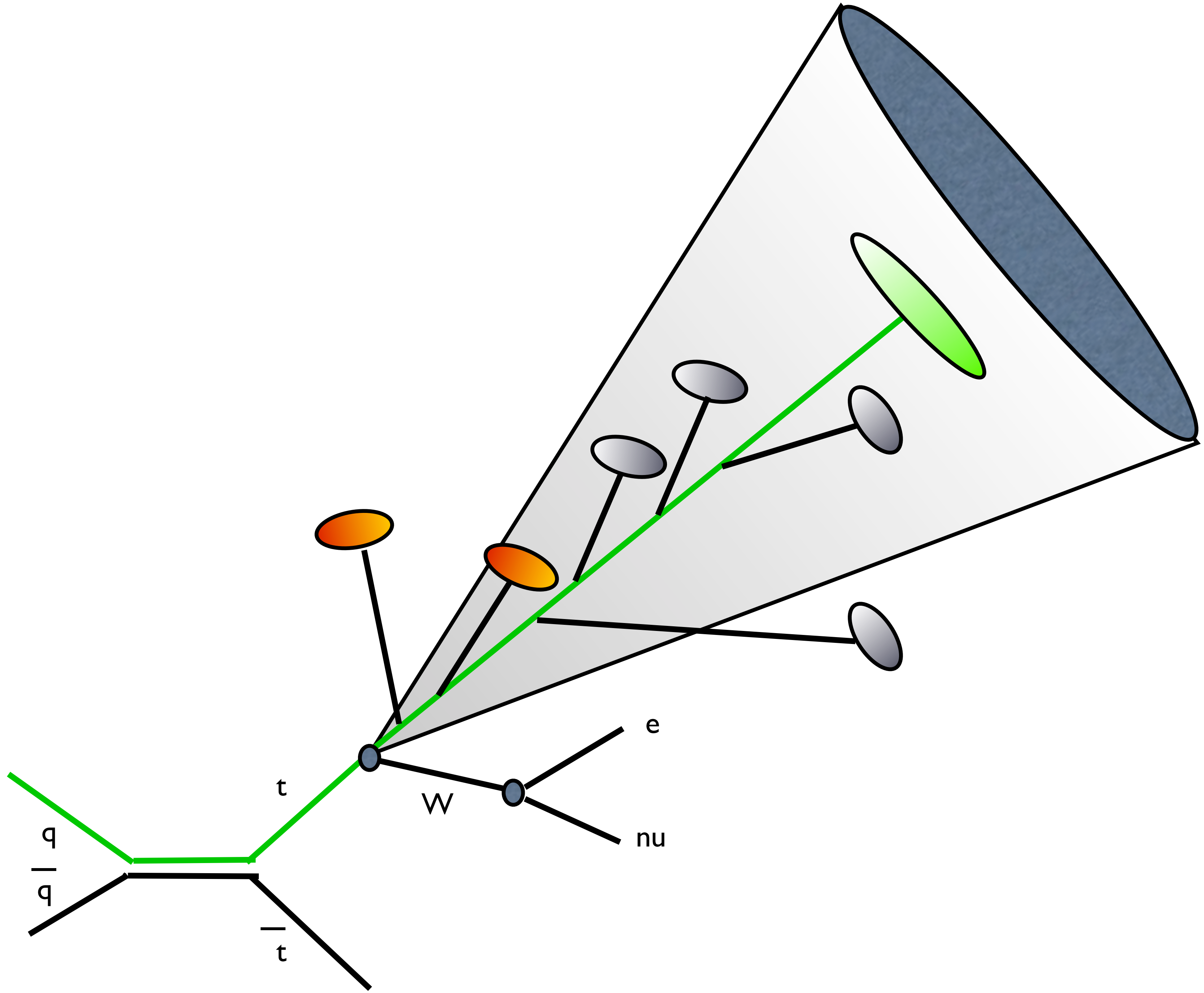
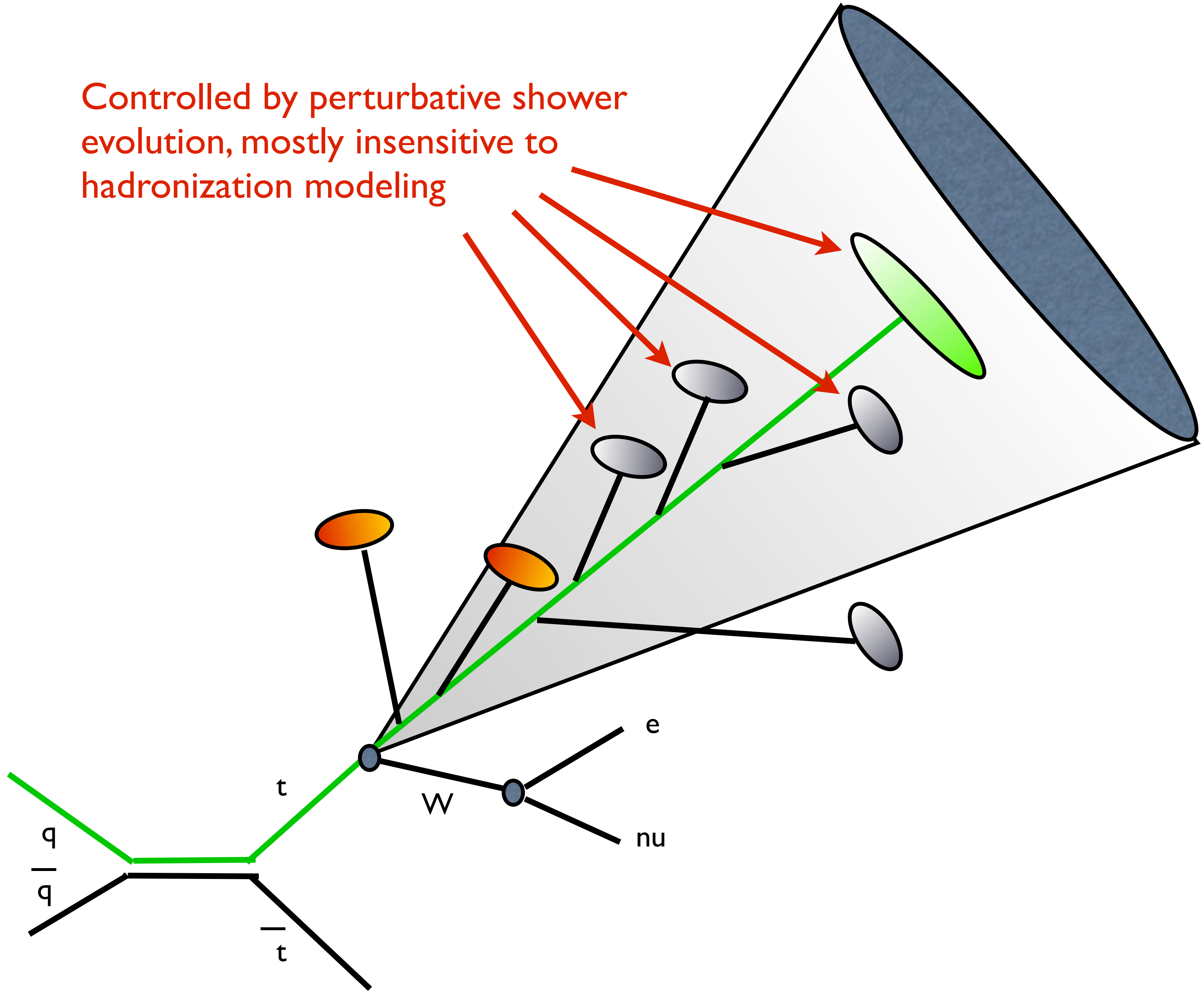
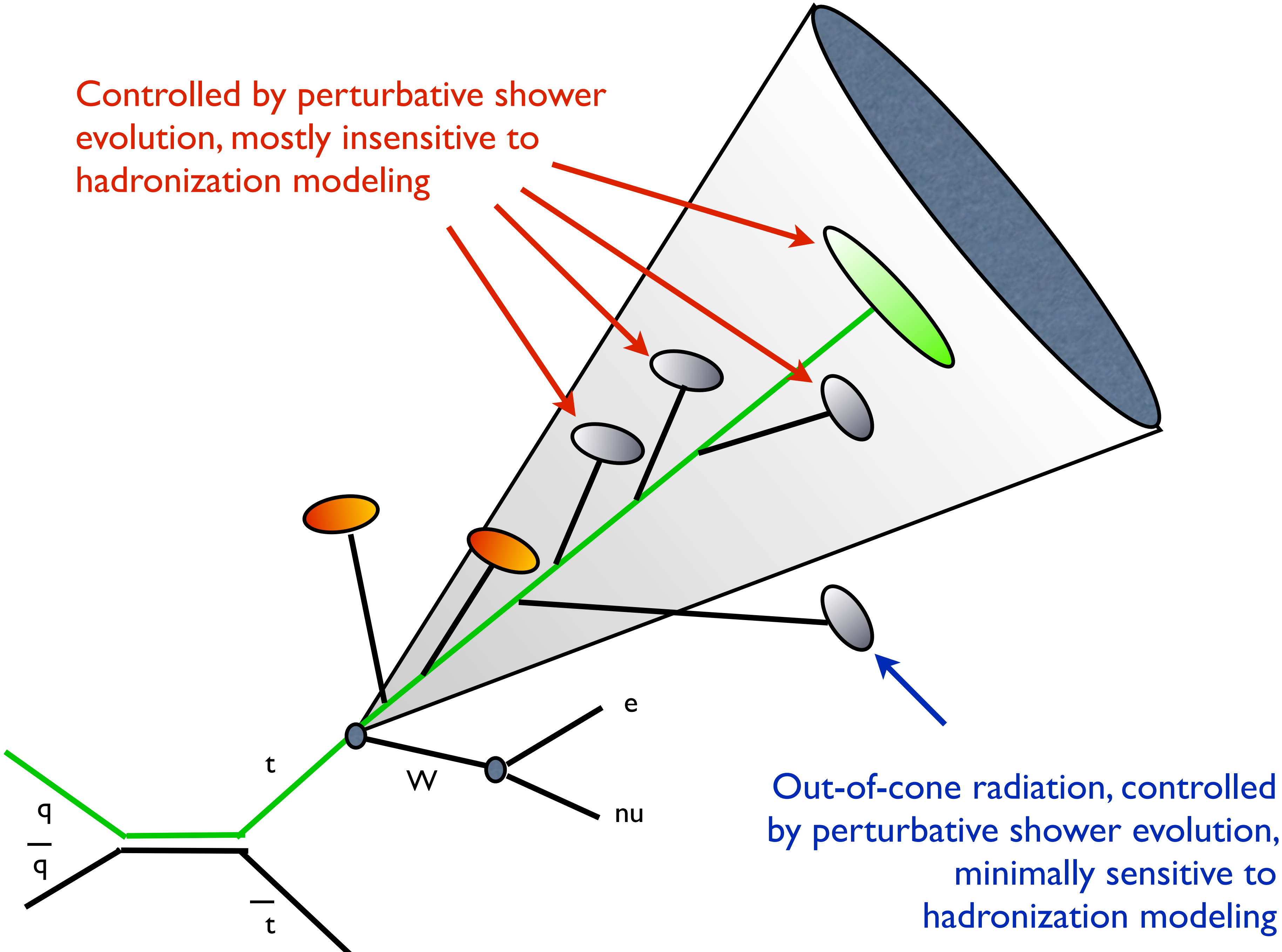
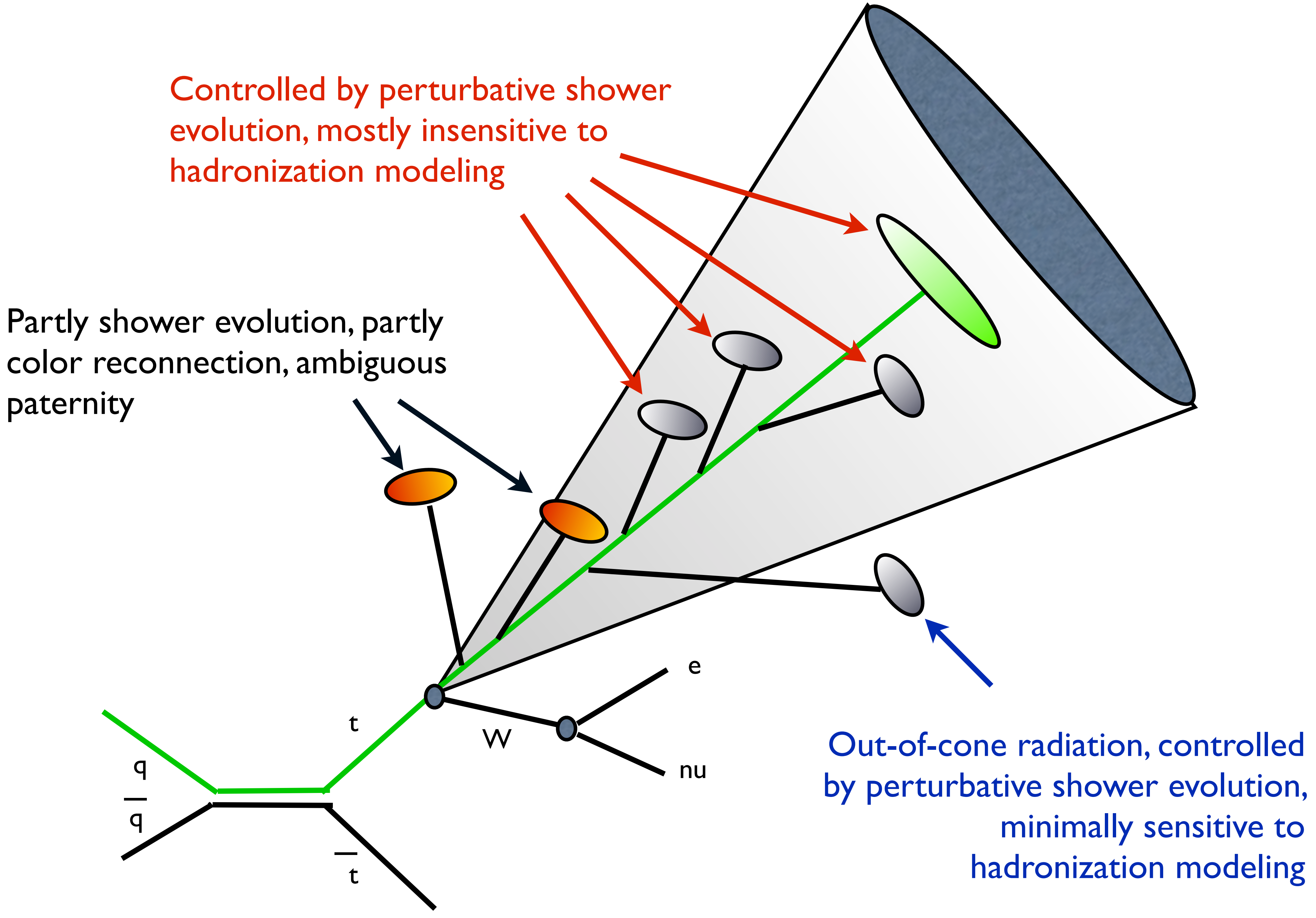


e
t
W
nu
q
q
t



Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling
e
t
W
nu
q
q̄
t̄


Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling
Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling
e
nu
W
t
q
q̄
t̄



Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling
Partly shower evolution, partly color reconnection, ambiguous paternity
Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling
t
W
e
nu
q
q̄
t̄

What is the impact, and what are the modeling uncertainties, due to the "odd" clusters?

How does their contribution to mtop depend on the top production dynamics and kinematics?

- gg vs qqbar initial state
- dependence on p_{top}
- LHC vs Tevatron

$$m_{top}^2 \text{ “=” } (p_W + p_{b\text{-jet}})^2$$

"=" : this relation defines a template distribution, whose shape depends on m_{top}^{MC}

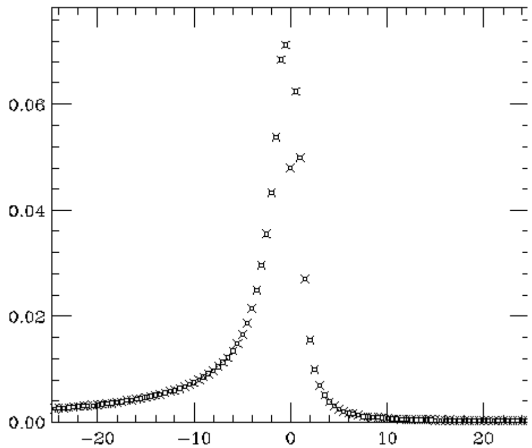
$$p_{b\text{-jet}} = p_{jet}(\text{even clusters}) + p_{jet}(\text{odd clusters})$$

define "jet" as clusters within $\Delta R<0.4$ from b-quark direction

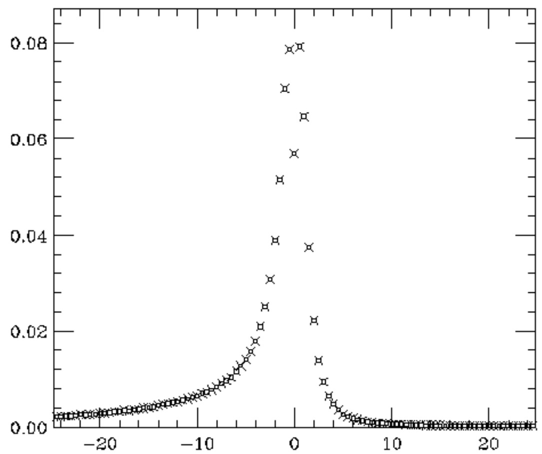
Example: m_{top} vs pt(top)

m_{top}(E+O) – 172.5

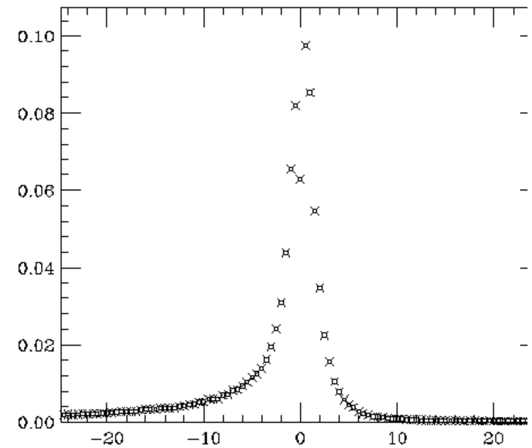
pt<100 GeV <>=–3.5 GeV



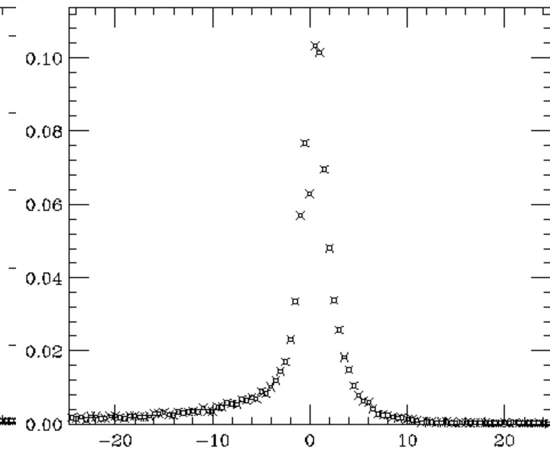
100<pt<200 <>=–2.8 GeV



200<pt<300 <>= –1.95 GeV

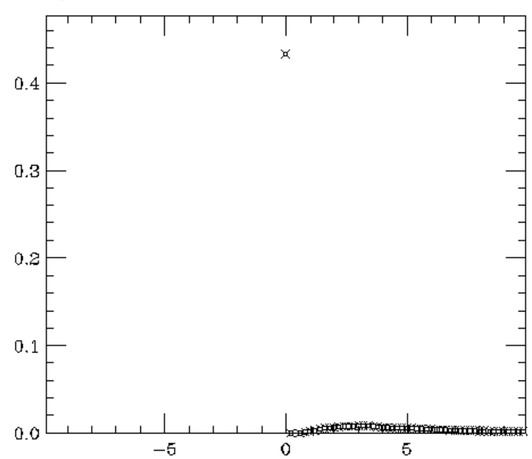


pt>300 <>= –0.98 GeV

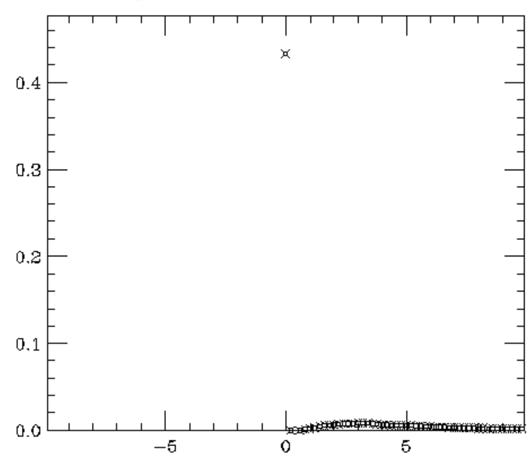


m_{top}(E+O) – m_{top}(E)

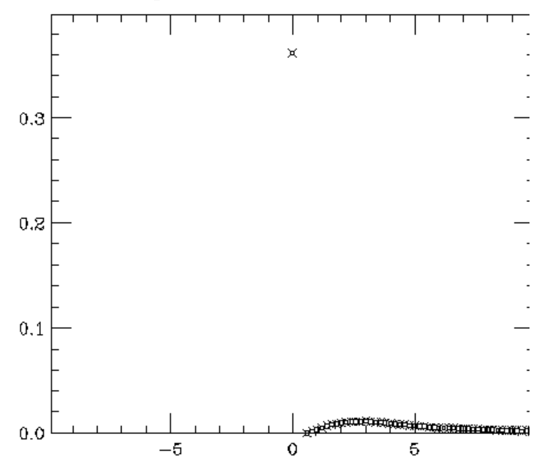
pt<100 GeV <>= 1.08 GeV



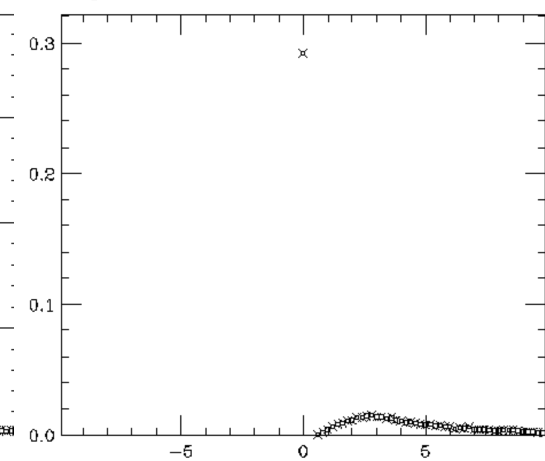
100<pt<200 <>= 1.38 GeV



200<pt<300 <>= 1.83 GeV



pt>300 <>= 2.24 GeV



Notation:

m_{top}(E+O): include both even and odd clusters

m_{top}(E): include only even

A good way to validate the modeling systematics using data is to monitor the dependence of the reconstructed m_{top} on the production environment. E.g.

- **m_{top} vs pt**

- **pp → t tbar implies that hadronization of top decay products differs from hadronization of tbar decay products ⇒ m_t vs m_{tbar} at the LHC probes possible hadronization systematics**

- **q qbar → t tbar vs gg → t tbar ⇒ m_{top}(Tevatron) vs m_{top}(LHC) is a probe of hadronization systematics**

- **ditto for m_{top} from single top events**

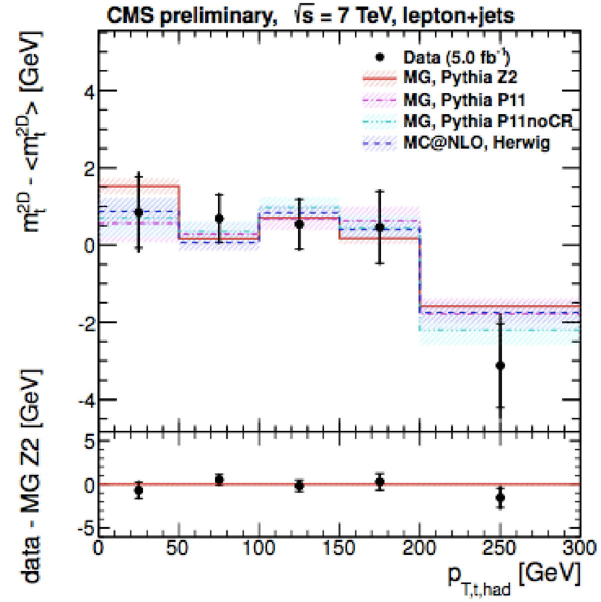
First studies of kinematical dependence of top mass reconstruction, CMS

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

NEW

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



- *First top mass measurement binned in kinematic observables.*
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS~ masses.

10

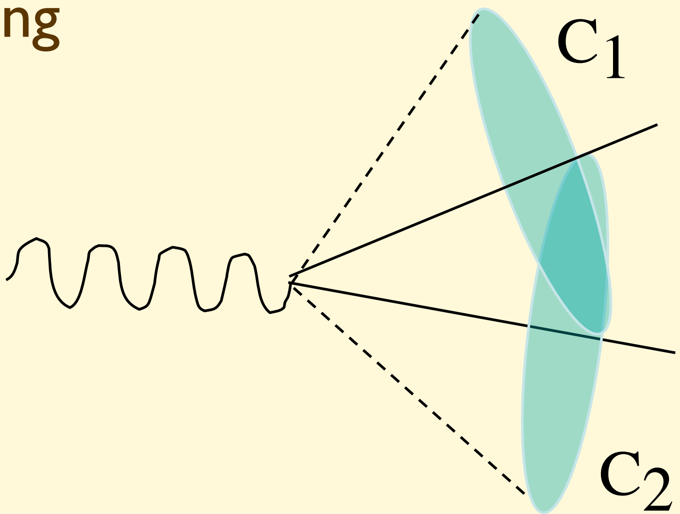
CMS-PAS-TOP-12-031

$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat) \pm 122\ (syst.)\ MeV$$

Multijet final states

Main limitation of shower approach:

Because of angular ordering



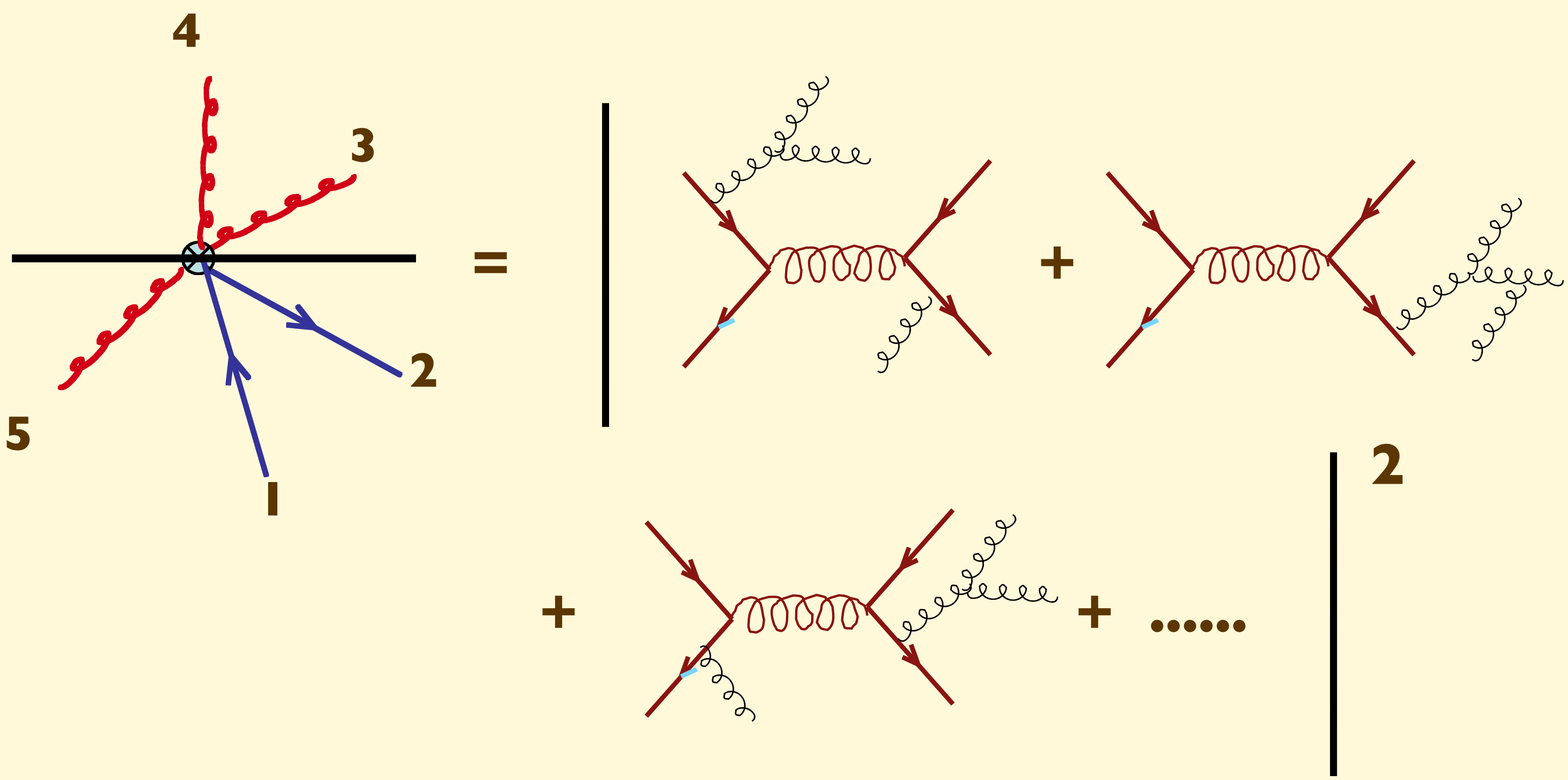
no emission outside $C_1 \oplus C_2$:

- lack of hard, large-angle emission
- poor description of multijet events

incoherent emission inside $C_1 \oplus C_2$:

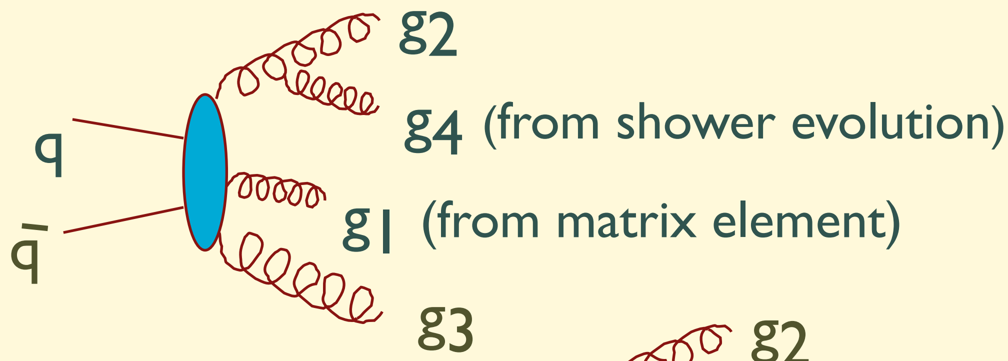
- loss of accuracy for intrajet radiation

The obvious solution is to start the shower from a higher-order process calculated at the parton level with the exact LO matrix element:



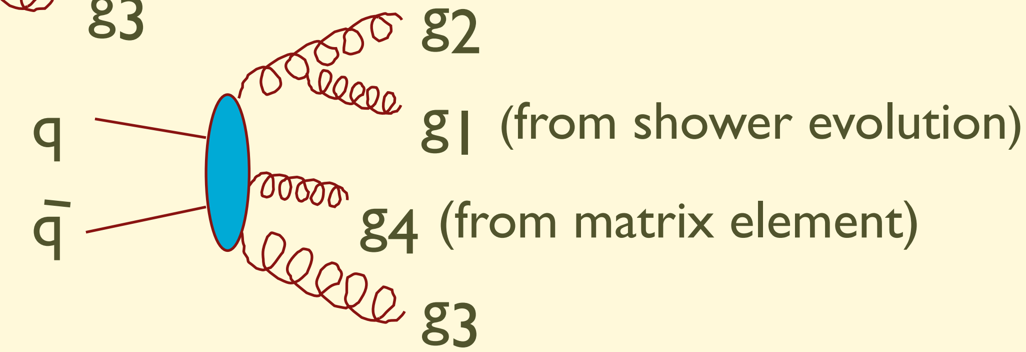
Each hard parton then undergoes the shower evolution according to the previous prescription.

This approach has its own problems:



with PT1 << PT4 << PT2, PT3

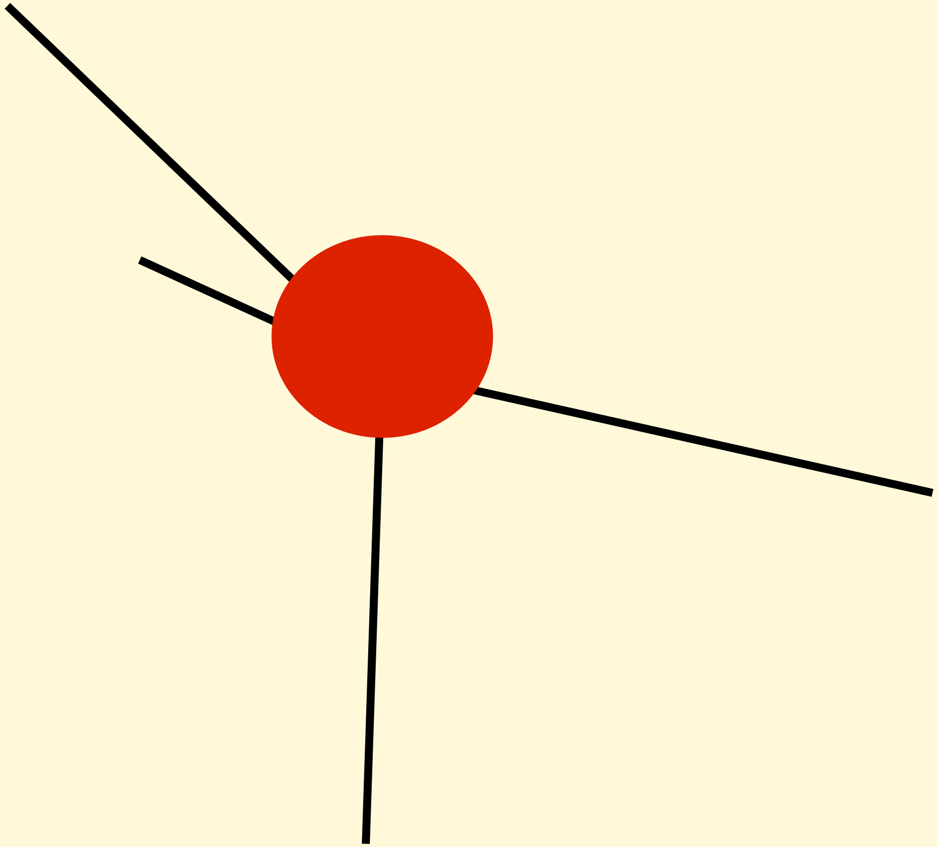
versus



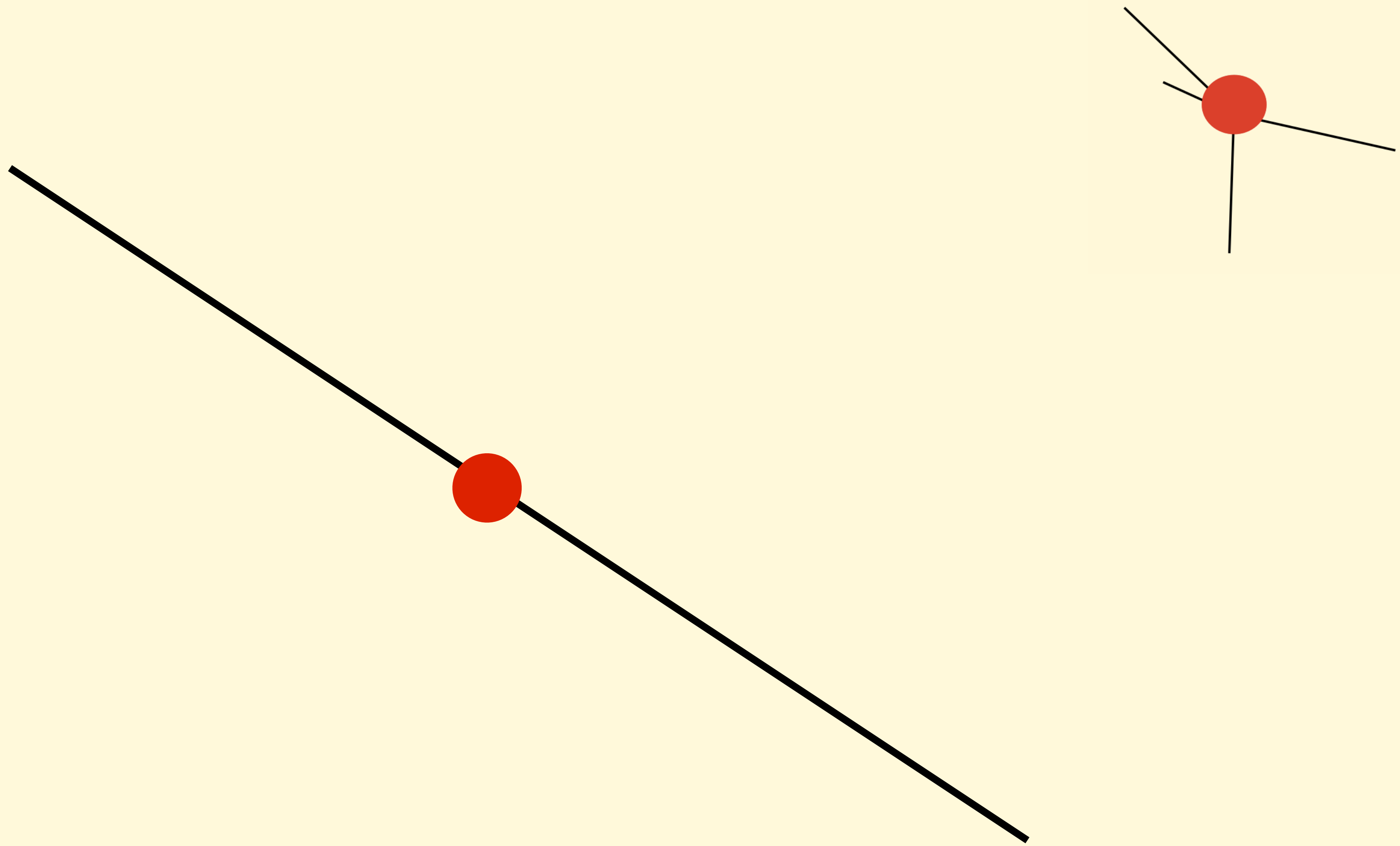
⇒ **double counting of the same phase-space points**

The solution to these problems goes under the name of matching algorithms, which allow to combine higher-order ME and shower evolution avoiding the double counting (“CKKW”, “MLM matching”)

Example: possible ways of generating a 4-body final state



Representation 1:
Double shower emission from a 2-parton final state



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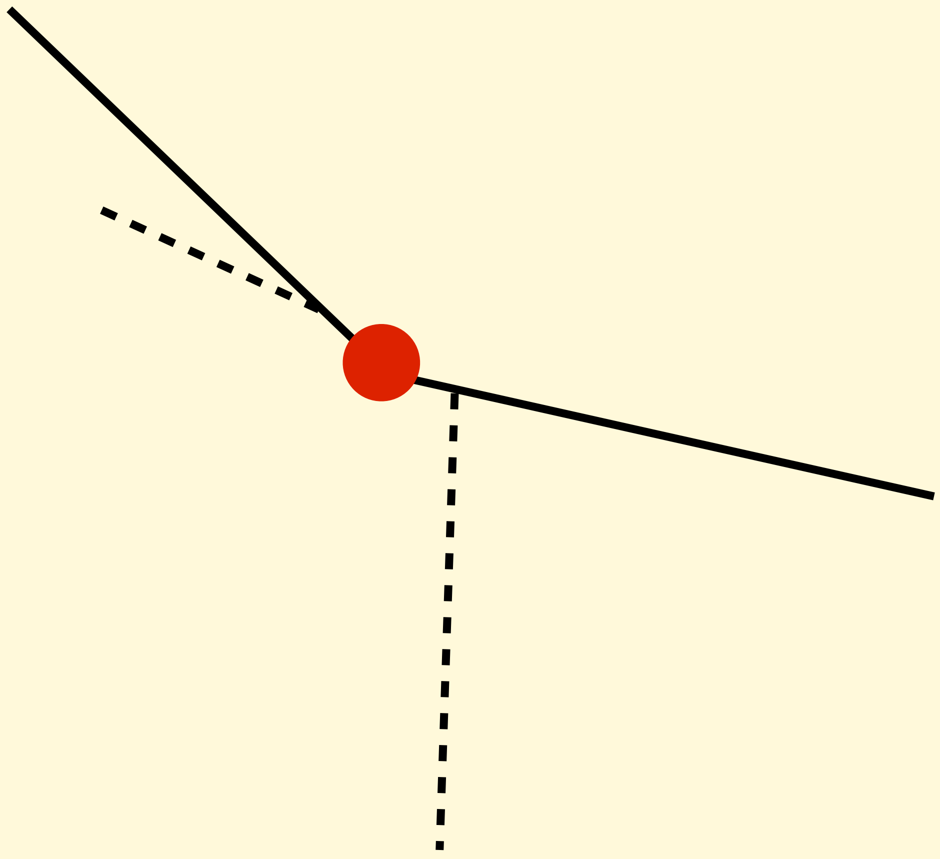

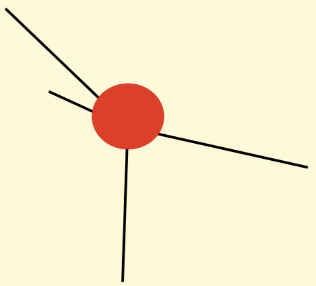

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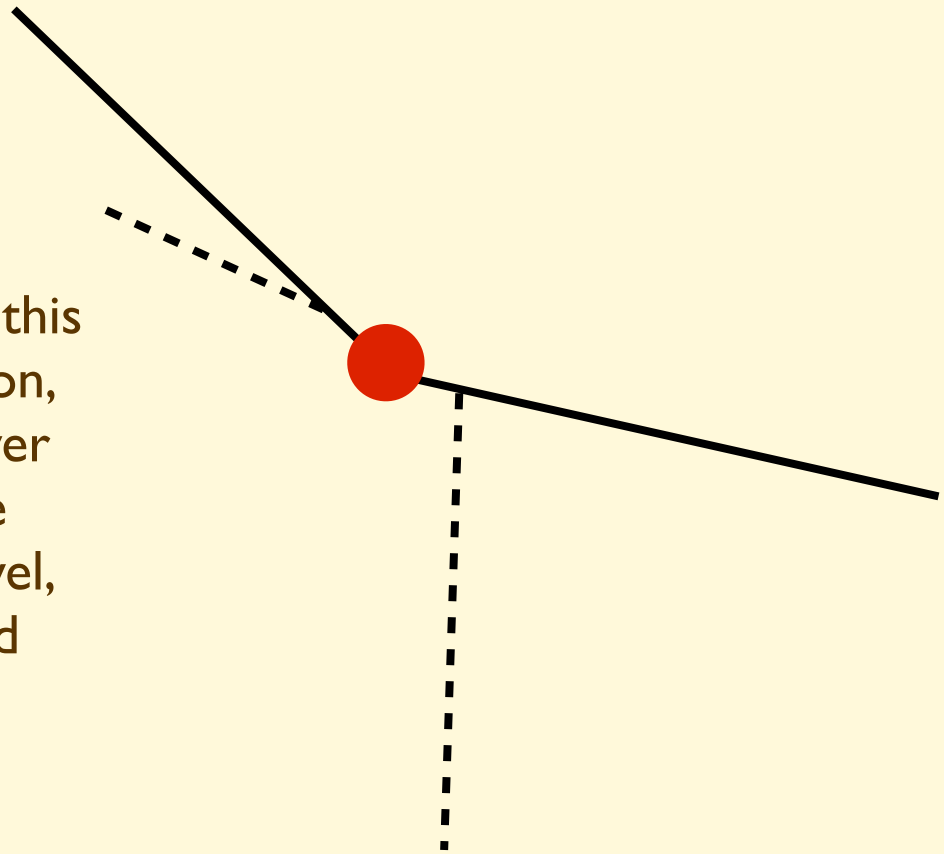
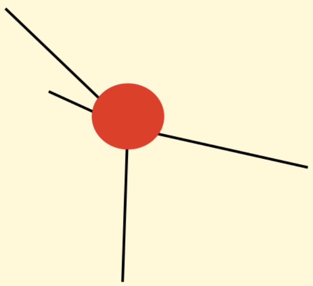
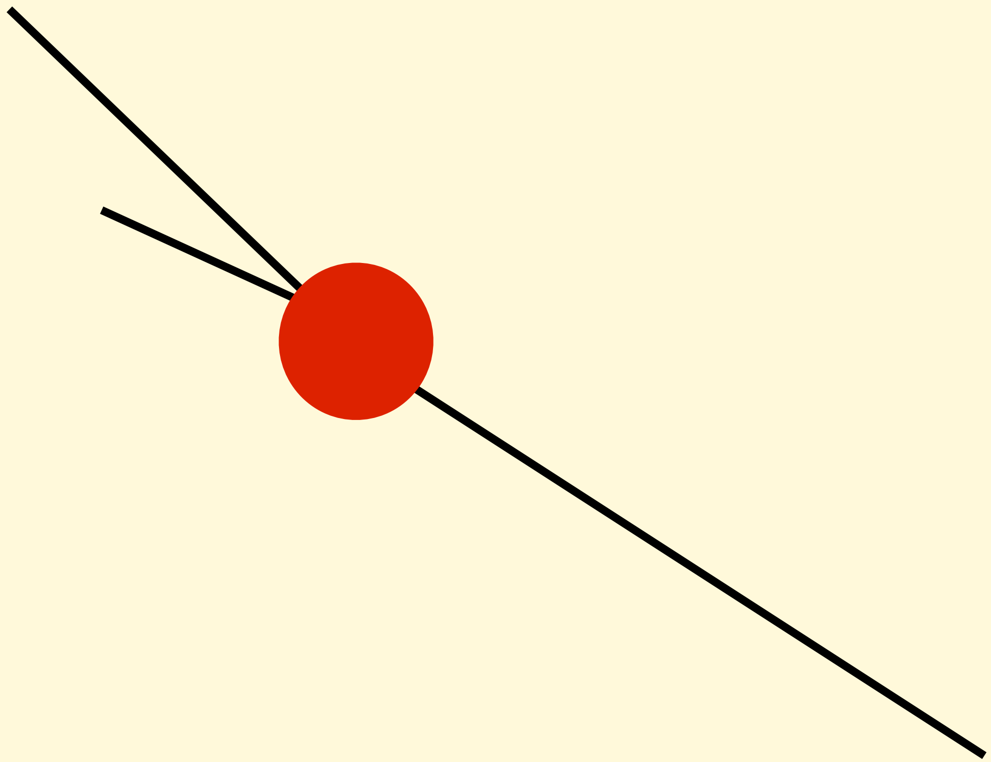


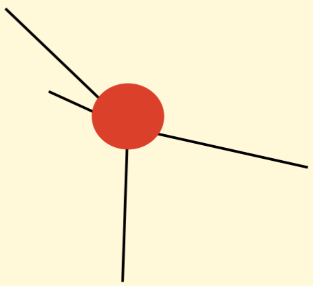


Good description of this ~collinear configuration, since it uses the shower (which includes, at the leading logarithmic level, virtual corrections and resummation)

Poor description of this emission, since it's hard and at large angle

Representation 2:
Shower emission from a 3-parton final state





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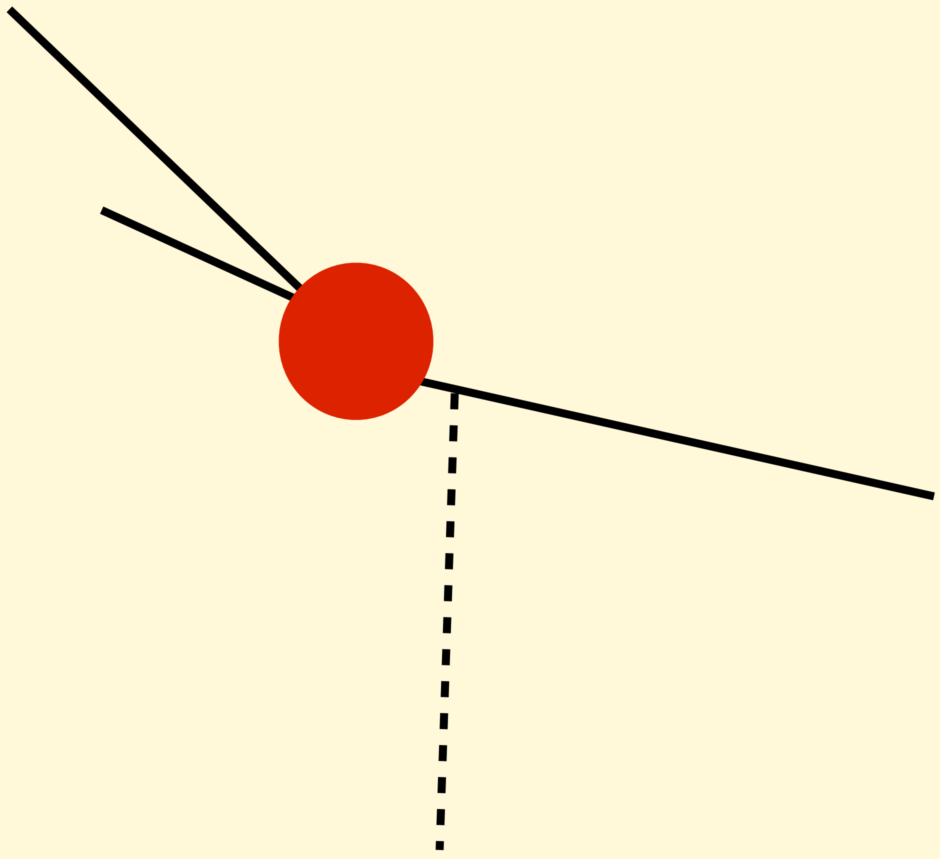

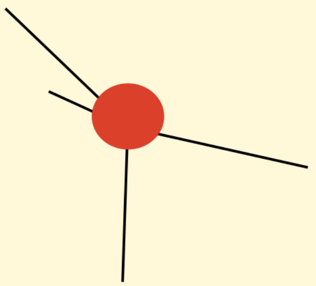

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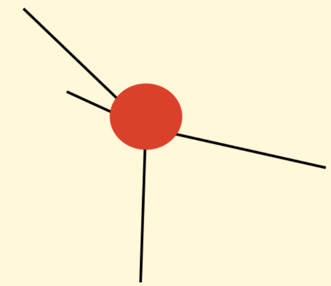
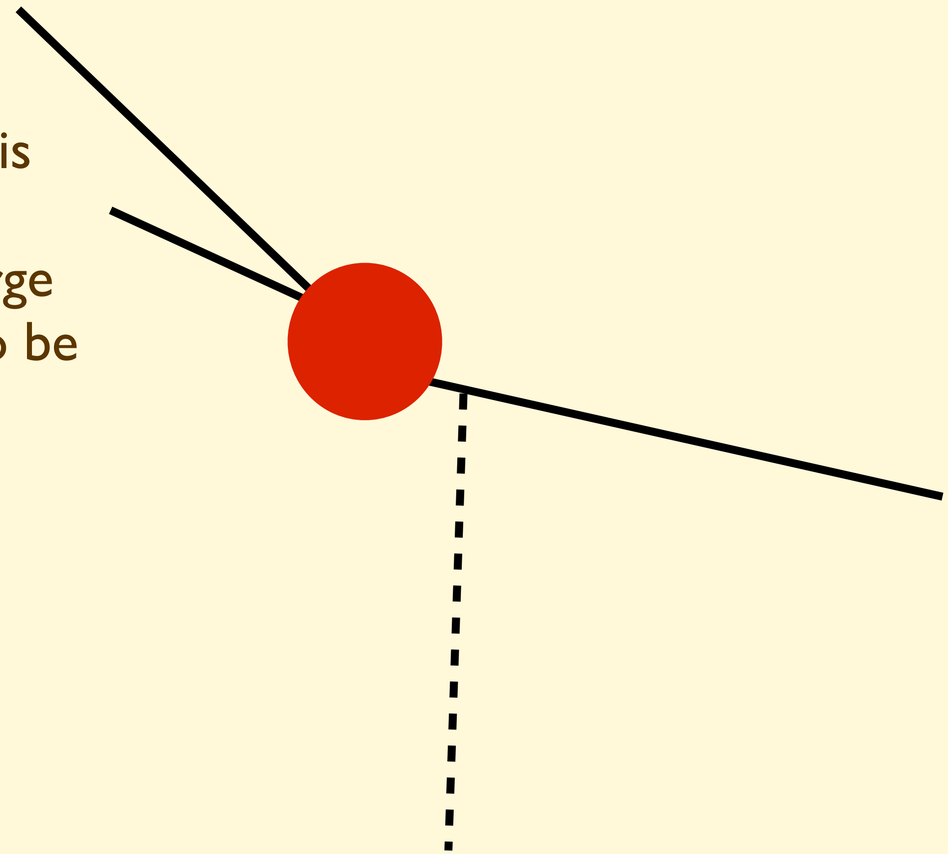
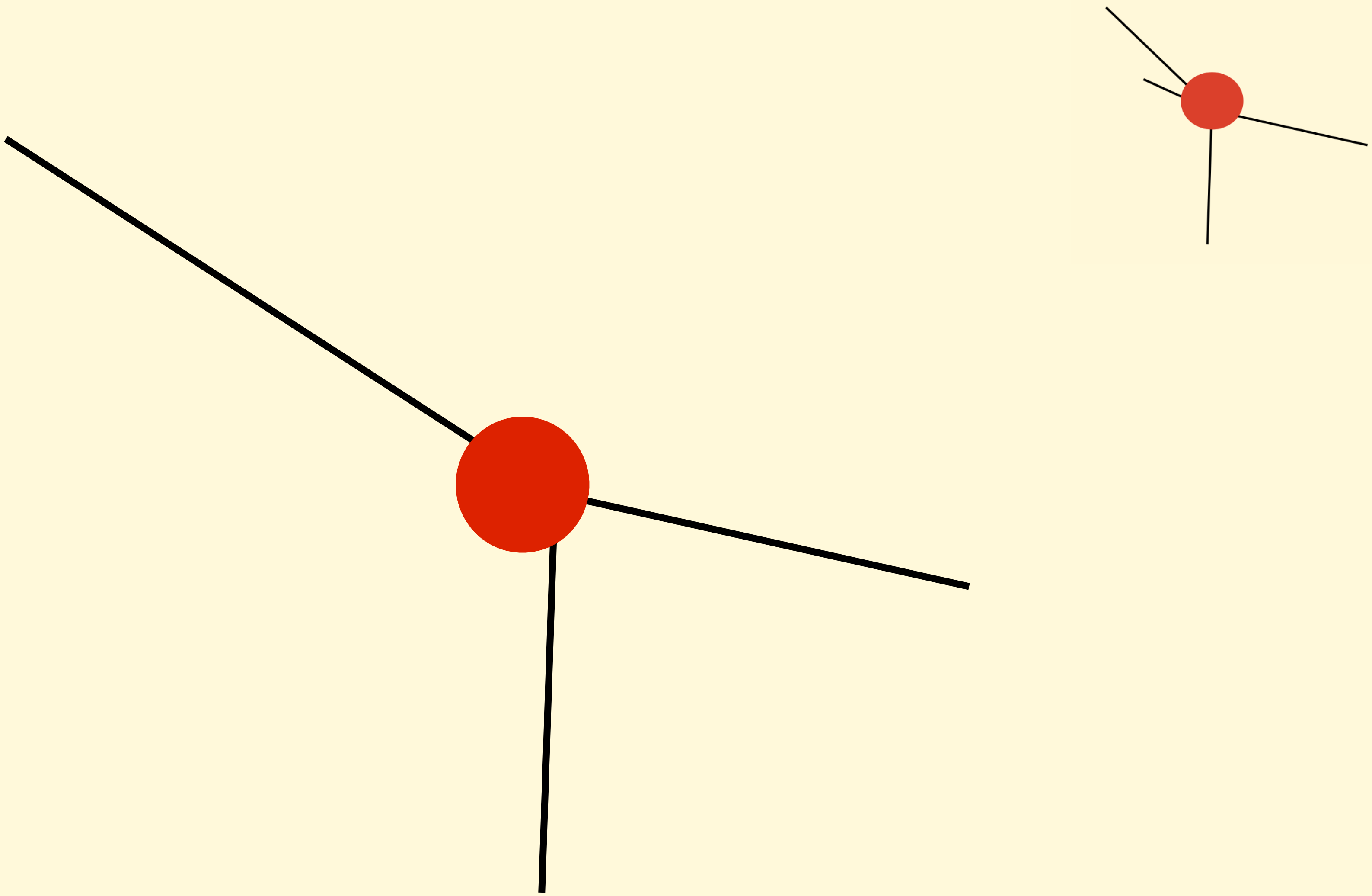


Poor description of this configuration, since it's ~collinear, leads to a large logarithm, that needs to be absorbed by virtual corrections and by resummation



Poor description of this emission, since it's hard and at large angle

Representation 3:
Shower emission from a different choice of 3-parton final state



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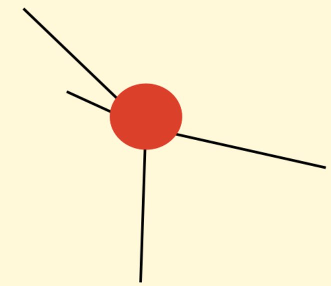

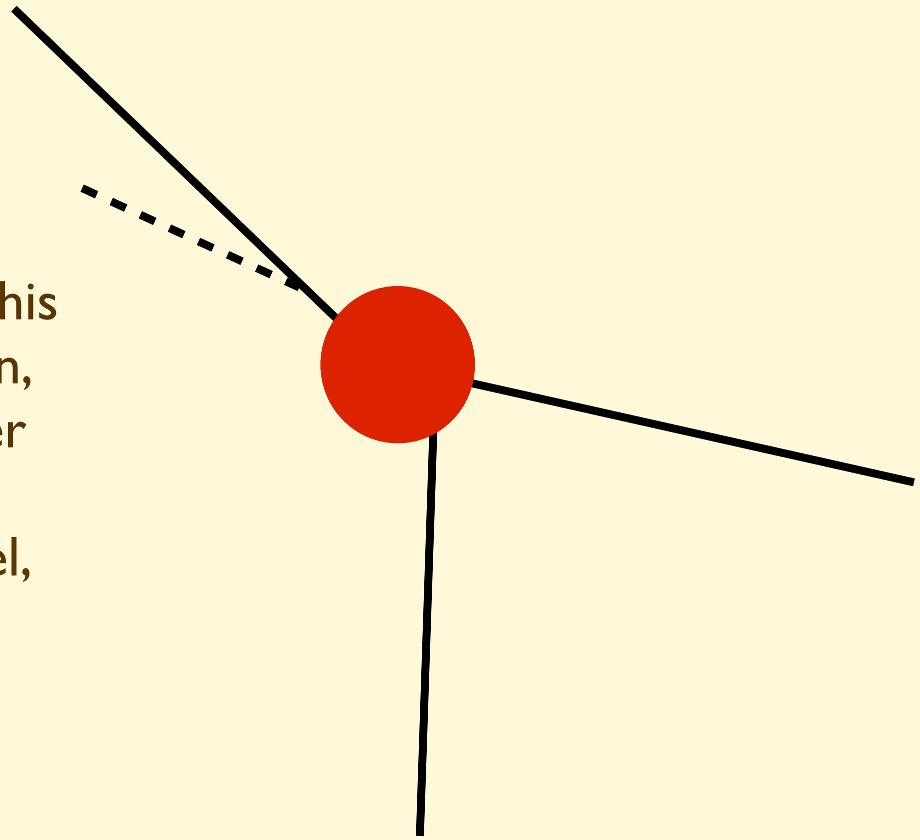

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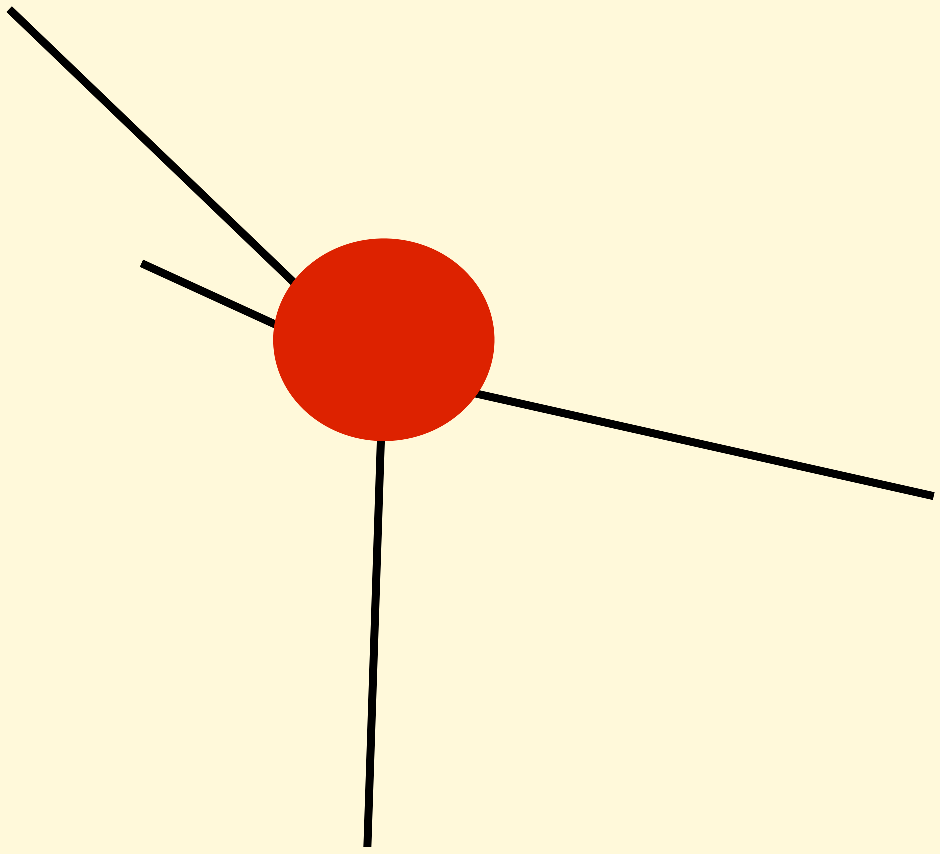
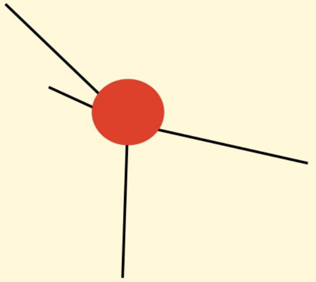
Good description of this hard/ large-angle emission, since it's using the matrix element

Representation 4:
Generated directly as a 4-parton final state





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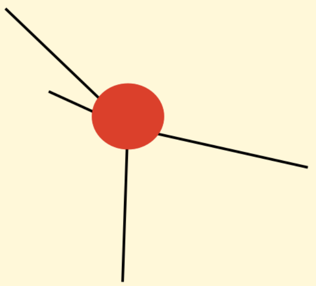

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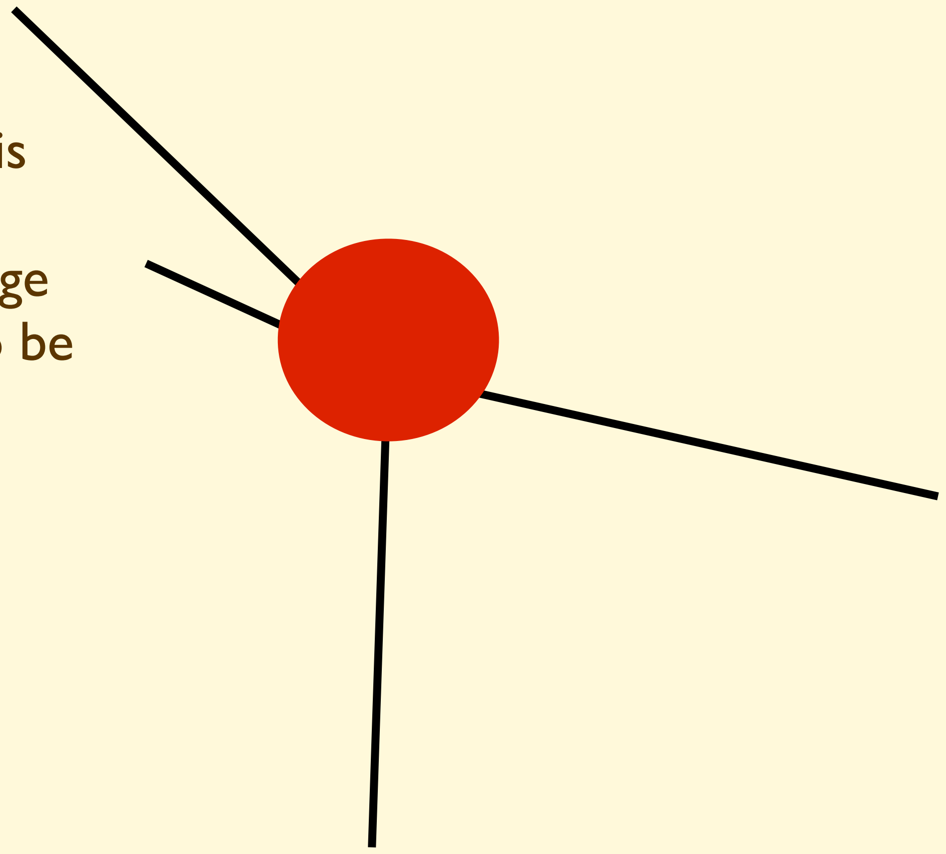

Good description of this hard/ large-angle emission, since it's using the matrix element

As we generate an inclusive sample of events, including events of any multiplicity, we should apply a "filter" (matching algorithm) that decides which representation gives the most accurate description of a given event. In our example, this means:

Event 1 ($2\to2$ plus double shower emission)	$\Rightarrow$ throw away
Event 2 ($2\to3$, config (a), plus shower emission)	$\Rightarrow$ throw away
Event 3 ($2\to3$, config (b), plus shower emission)	$\Rightarrow$ **keep**
Event 4 ($2\to4$)	$\Rightarrow$ throw away

MLM merging algorithm for multijet final states

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- **Generate parton-level configurations** for a given hard-parton multiplicity N_{part}, with partons constrained by $p_T > p_{T,min}$ and $\Delta R_{jj} > R_{min}$

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- **Perform the parton shower and reconstruct jets** (before hadronization) with a jet algorithm, (e.g. a cone algorithm, defined by $E_{T,min} \sim p_{T,min}$ and $R \sim R_{min}$)

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- **Match hard partons and jets:**

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MLM merging algorithm for multijet final states

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  - else, keep the event, if the unmatched additional jets are softer than all matched jets (this defines an inclusive sample with $N_{jets} \geq N_{part}$)

MLM merging algorithm for multijet final states

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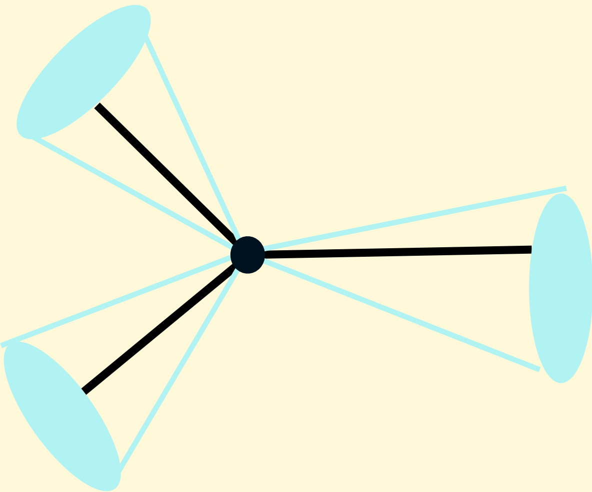
  - else, keep the event, if the unmatched additional jets are softer than all matched jets (this defines an inclusive sample with $N_{jets} \geq N_{part}$)
- After matching, combine all samples to obtain an **inclusive sample containing events with all multiplicities**

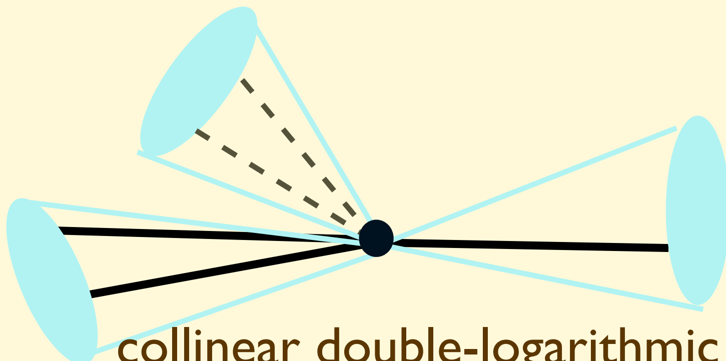
Few examples of matching:

— hard parton

- - - parton emitted by the shower



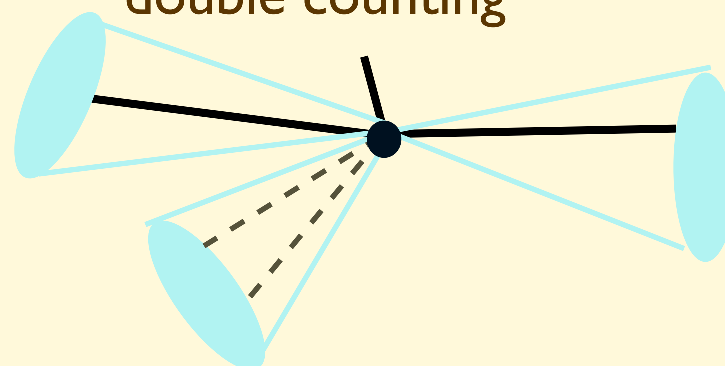
Event matched, $N_{jet}=N_{part}=3$, keep

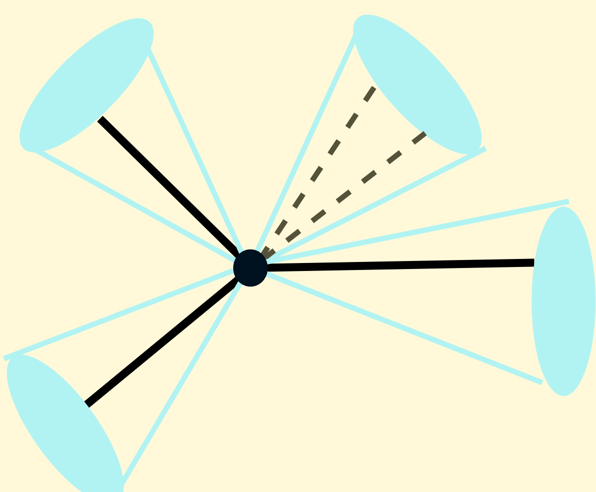


collinear double-logarithmic double counting

NOT matched, $N_{jet}=N_{part}=3$, but $N_{match}=2$ Throw away

soft single-logarithmic double counting





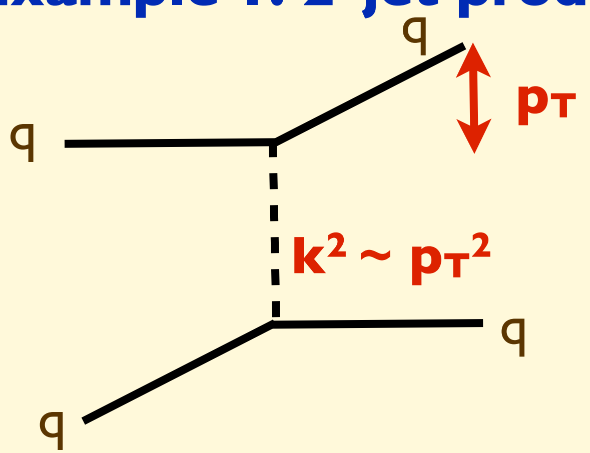
Event matched, $N_{jet}>N_{part}$:

o Keep for inclusive sample **if the unmatched jet is softer than all matched ones**.

o Throw away otherwise, or for exclusive samples.

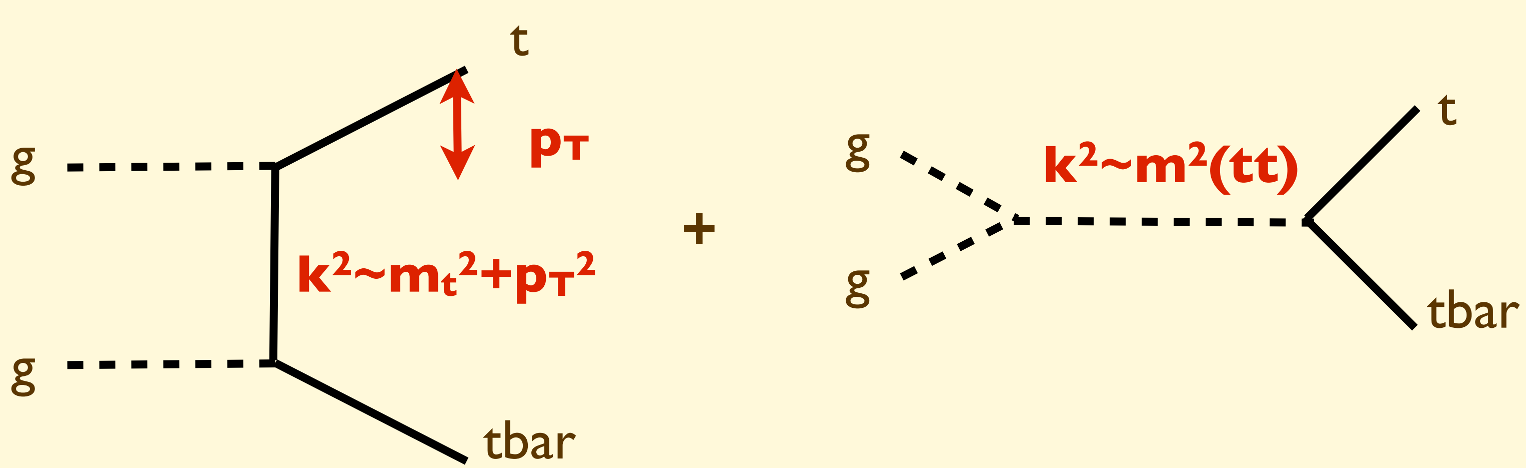
Issues in setting the proper scale for $\alpha_S(Q^2)$

Example 1: 2-jet production



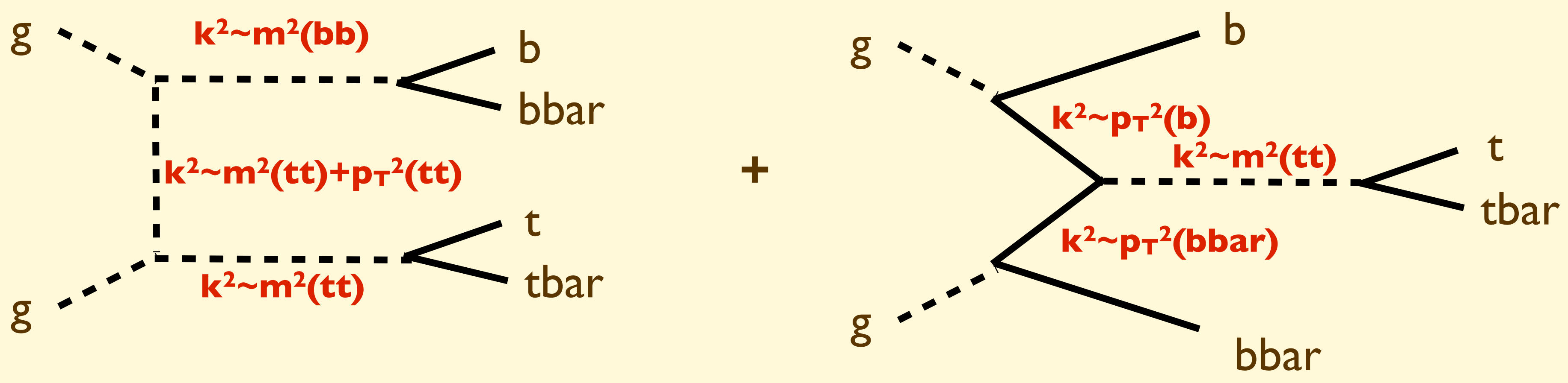
⇒ $Q=p_T$ is the natural, and only, scale present in this process

Example 2: t-tbar production



⇒ Here we have two scales, $Q_a^{\ 2} = m_t^2 + p_T^2$ and $Q_b^{\ 2} = m^2(t\text{-tbar})$. However they are numerically similar ⇒ small difference in using $\alpha_S(Q_a)$ vs $\alpha_S(Q_b)$

Example 3: t tbar + b bbar production



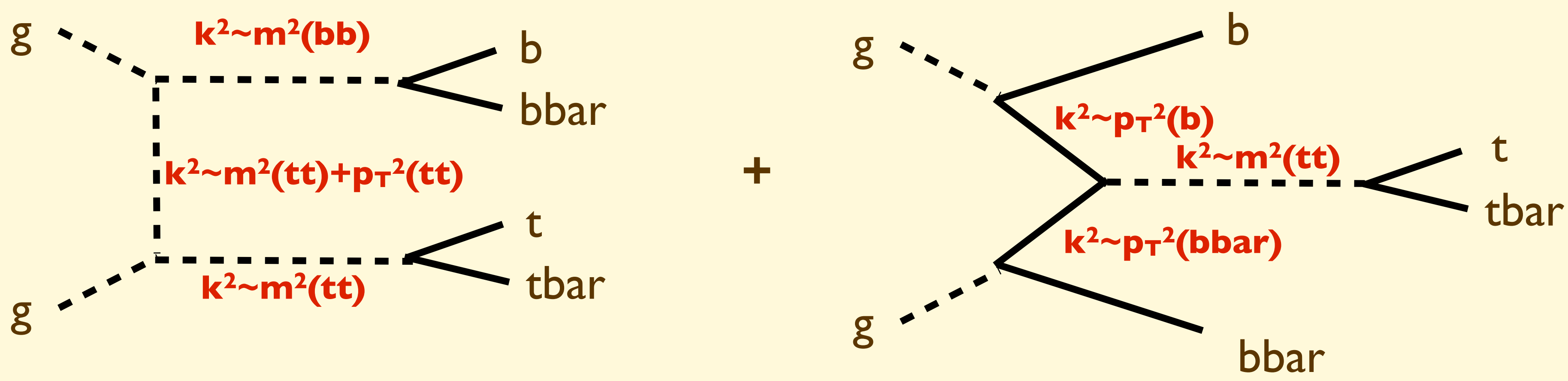
+ ....

⇒ Now we have several scales, which can be numerically very very different. E.g. we can certainly have kinematical configurations with **$p_T(b) << m(bb) << m(tt)$**

⇒ What is the right scale to be used for all 4 powers of $\alpha_S(Q)$ appearing in the cross section ??

$[\ \alpha_S(2m_{bottom})/\alpha_S(2m_{top})\ ]^4 \sim 16$!!

Example 3: t tbar + b bbar production



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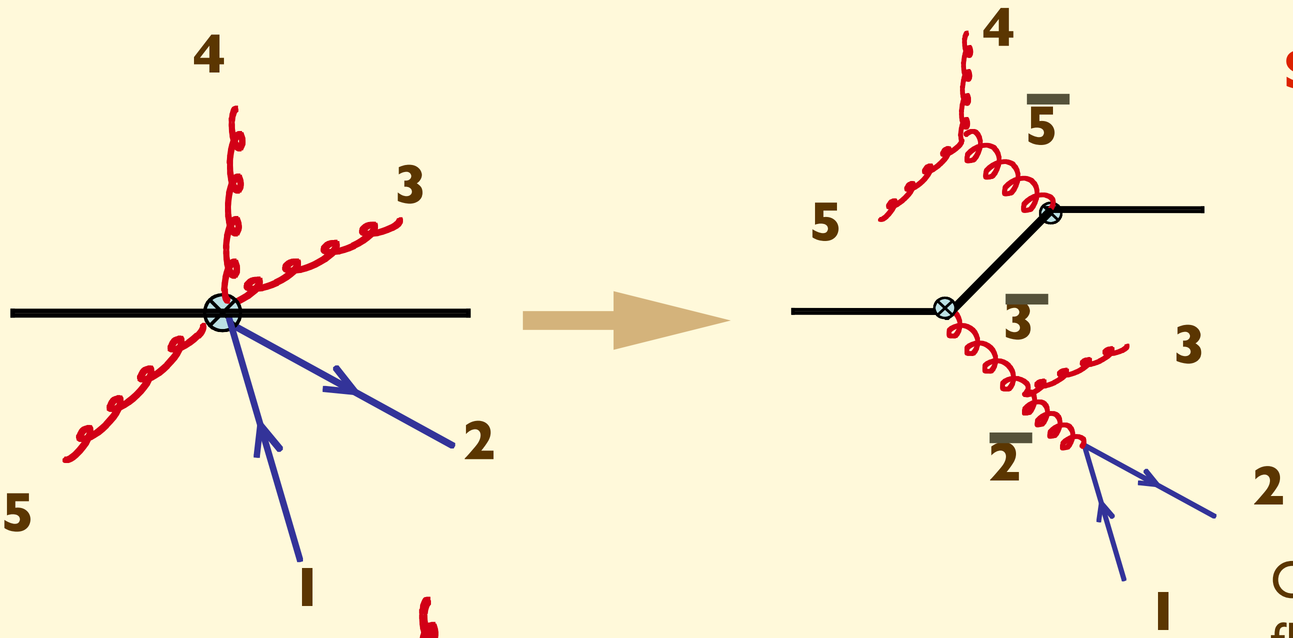
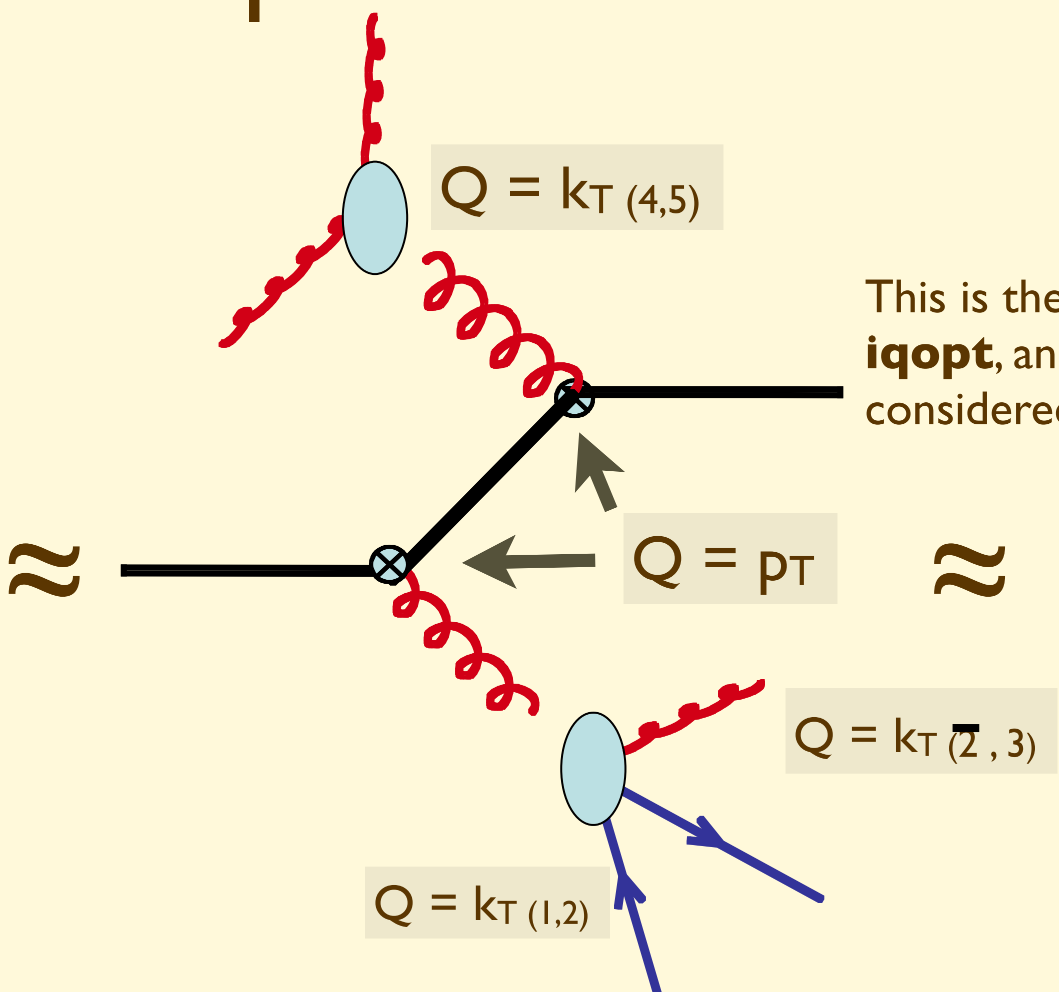
Similar problems arise each time we deal with multijet final states, in configurations with multiple mass scales

Scale setting in calculations with matching
(a.k.a. CKKW scale setting)



$k_{T[1,2]} < k_{T[\bar{2},3]} < k_{T[4,5]}$

Only pairings allowed by colour and flavour flows are considered



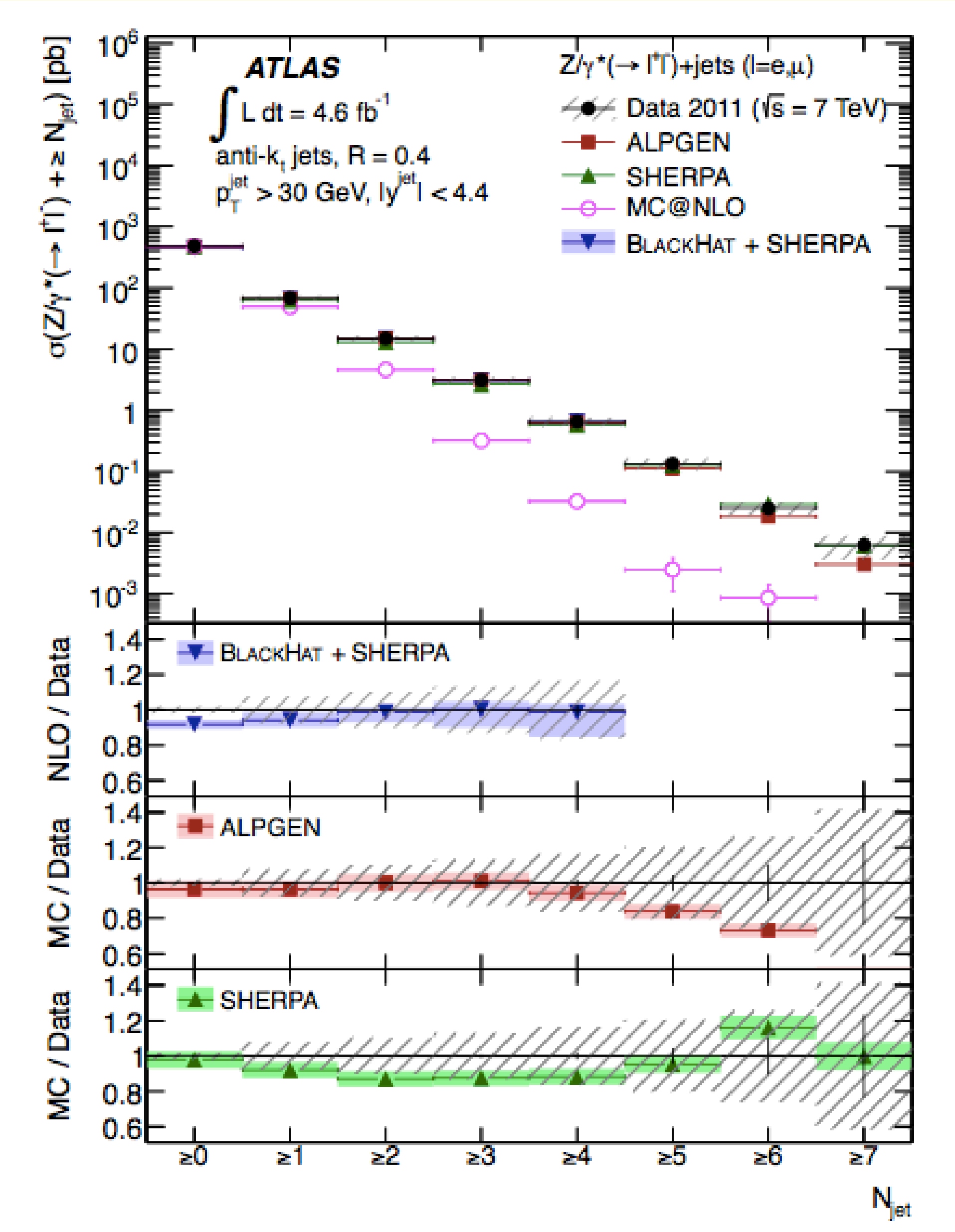
This is the hard scale as defined by **iqopt**, and depends on the hard process considered

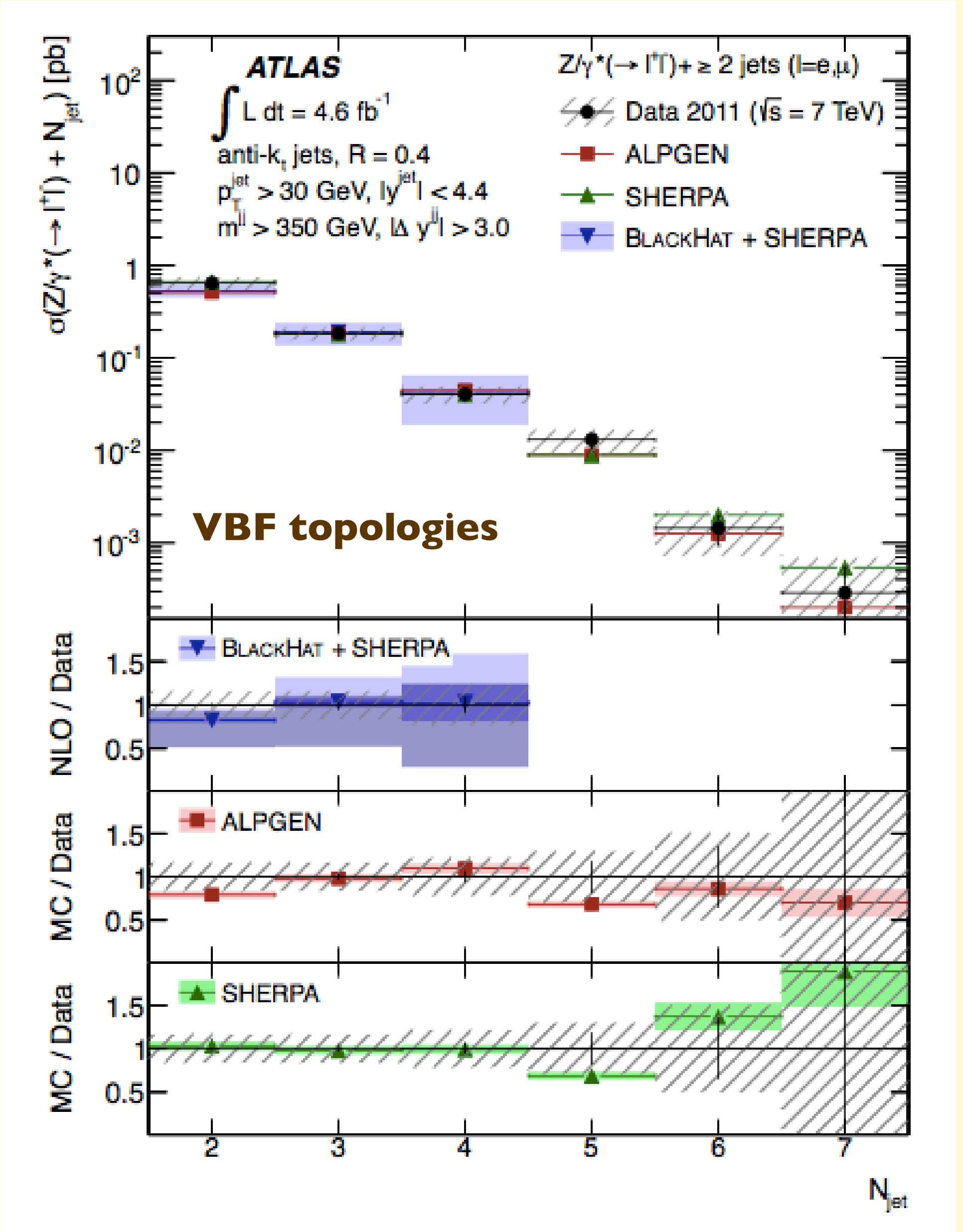
$$\approx \alpha^2 (p_T) \;\; \alpha (k_{T\,(1,2)}) \; \alpha (k_{T\,(12\,,\,3)}) \; \alpha (k_{T\,(4,5)})$$

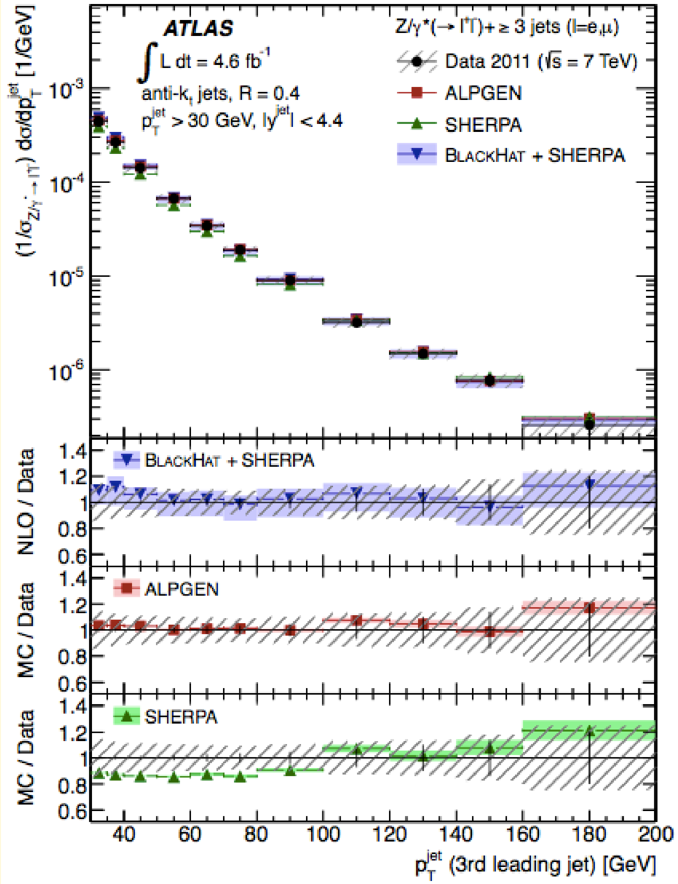
$$\otimes \; F_1 (x_1, p_T) \otimes \; F_2 (x_2, p_T)$$

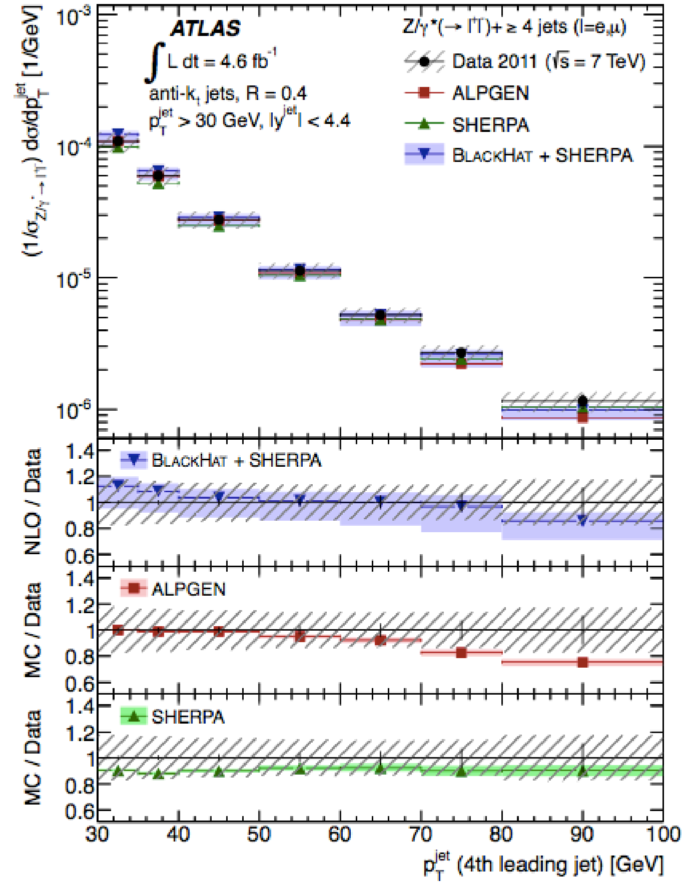
Examples: Z+jets, data vs theory

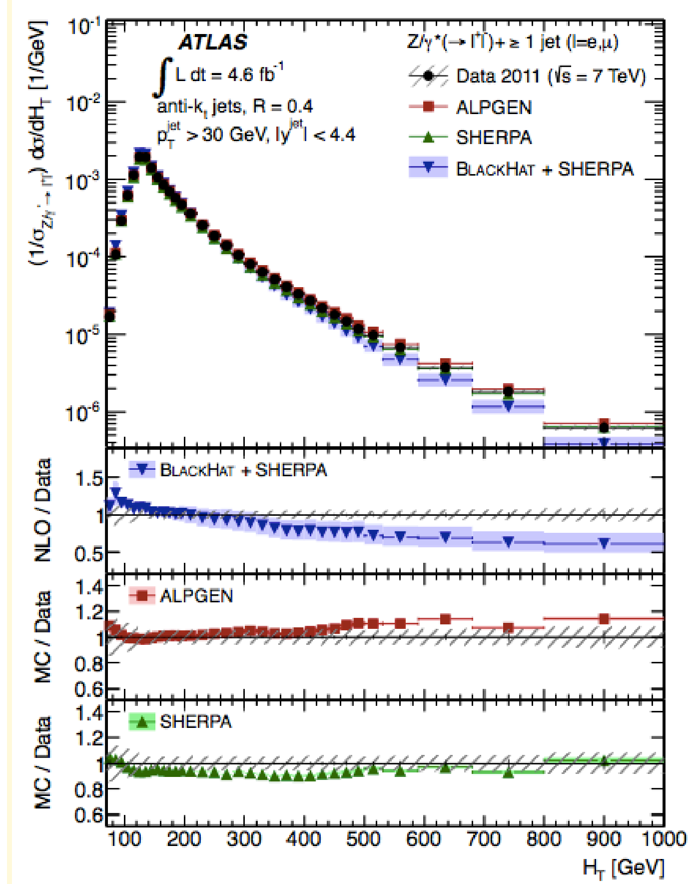
ATLAS, arXiv:1304.7098

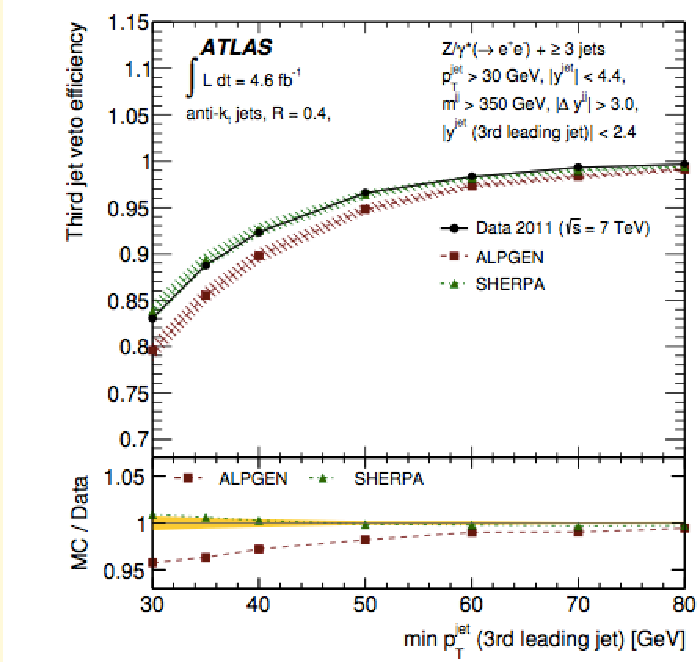


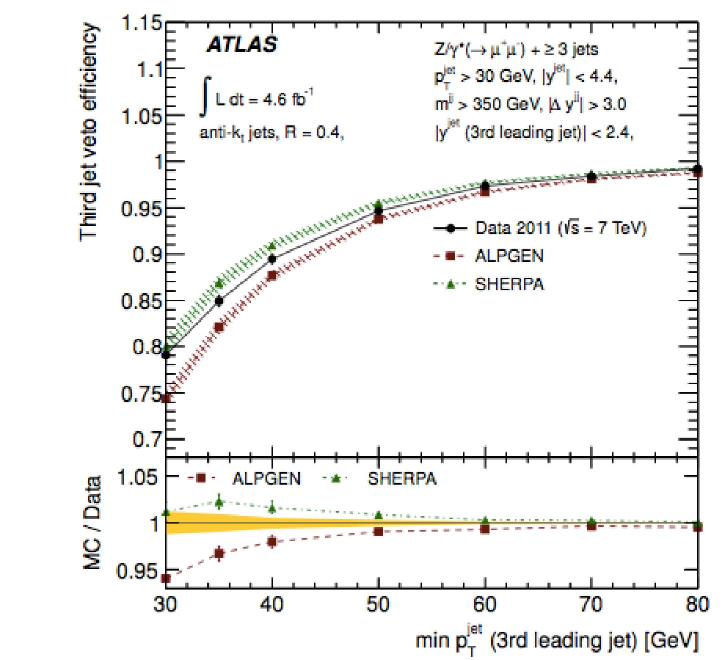



ATLAS
∫L dt = 4.6 fb⁻¹
anti-k_t jets, R = 0.4
p_T^jet > 30 GeV, |y^jet| < 4.4
Z/γ*(→ l⁺l⁻)+ ≥ 3 jets (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
BLACKHAT + SHERPA
(1/σ_Z/γ*→l⁺l⁻) dσ/dp_T^jet [1/GeV]
NLO / Data
MC / Data
p_T^jet (3rd leading jet) [GeV]


ATLAS
∫L dt = 4.6 fb⁻¹
anti-k_t jets, R = 0.4
p_T^jet > 30 GeV, |y^jet| < 4.4
Z/γ*(→ l⁺l⁻)+ ≥ 4 jets (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
BLACKHAT + SHERPA
(1/σ_Z/γ*→l⁺l⁻) dσ/dp_T^jet [1/GeV]
NLO / Data
MC / Data
p_T^jet (4th leading jet) [GeV]


ATLAS
∫L dt = 4.6 fb⁻¹
anti-k_t jets, R = 0.4
p_T^jet > 30 GeV, |y^jet| < 4.4
Z/γ*(→ l⁺l⁻)+ ≥ 1 jet (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
BLACKHAT + SHERPA
(1/σ_Z/γ*→l⁺l⁻) dσ/dH_T [1/GeV]
NLO / Data
MC / Data
H_T [GeV]


ATLAS
∫L dt = 4.6 fb⁻¹
anti-k_t jets, R = 0.4,
Z/γ*(→ e⁺e⁻) + ≥ 3 jets
p_T^jet > 30 GeV, |y^jet| < 4.4,
m^jj > 350 GeV, |Δ y^jj| > 3.0,
|y^jet (3rd leading jet)| < 2.4
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
Third jet veto efficiency
MC / Data
min p_T^jet (3rd leading jet) [GeV]


ATLAS
∫L dt = 4.6 fb⁻¹
anti-k_t jets, R = 0.4,
Z/γ*(→ μ⁺μ⁻) + ≥ 3 jets
p_T^jet > 30 GeV, |y^jet| < 4.4,
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Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
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MC / Data
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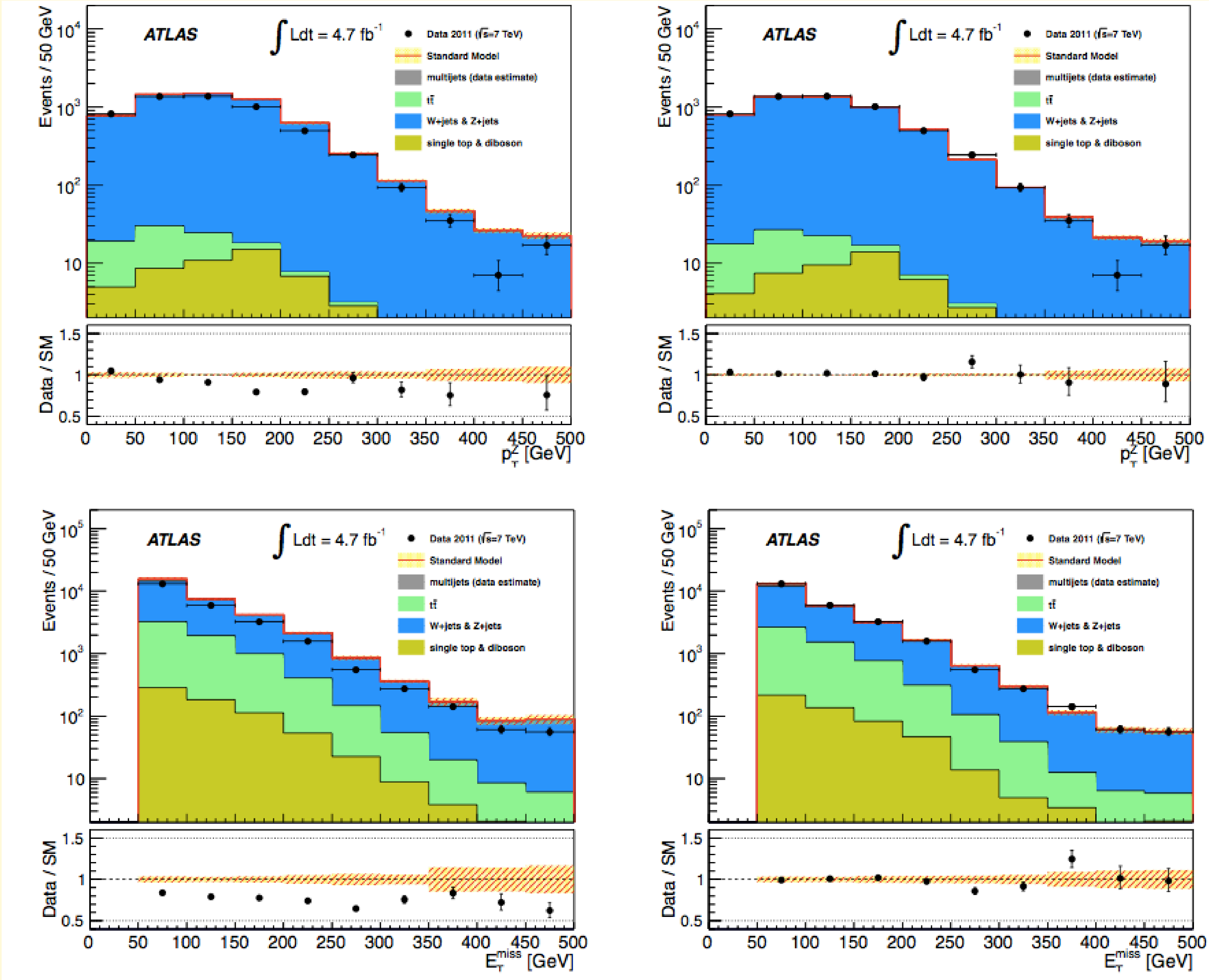
ATLAS
∫ Ldt = 4.7 fb⁻¹
Data 2011 (√s=7 TeV)
Standard Model
multijets (data estimate)
tt̄
W+jets & Z+jets
single top & diboson
Events / 50 GeV
Data / SM
p_T^Z [GeV]
ATLAS
∫ Ldt = 4.7 fb⁻¹
Data 2011 (√s=7 TeV)
Standard Model
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Events / 50 GeV
Data / SM
E_T^{miss} [GeV]
ATLAS
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W+jets & Z+jets
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Events / 50 GeV
Data / SM
E_T^{miss} [GeV]

Using LHC data to improve our knowledge about PDF

Example: precision Higgs physics

Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

14 TeV	δ(pert. theory)	δ(PDF, α_S)
gg→H	± 10 %	± 7%
VBF (WW→H)	± 1 %	± 2%
qq→WH	± 0.5 %	± 4%
(qq,gg)→ZH	± 2 %	± 4%
(qq,gg)→ttH	± 8 %	± 9%

Improve with higher-loop calculations:
gg->H @ NNNLO
ttH @ NNLO

Improve with dedicated QCD measurements, and appropriate calculations

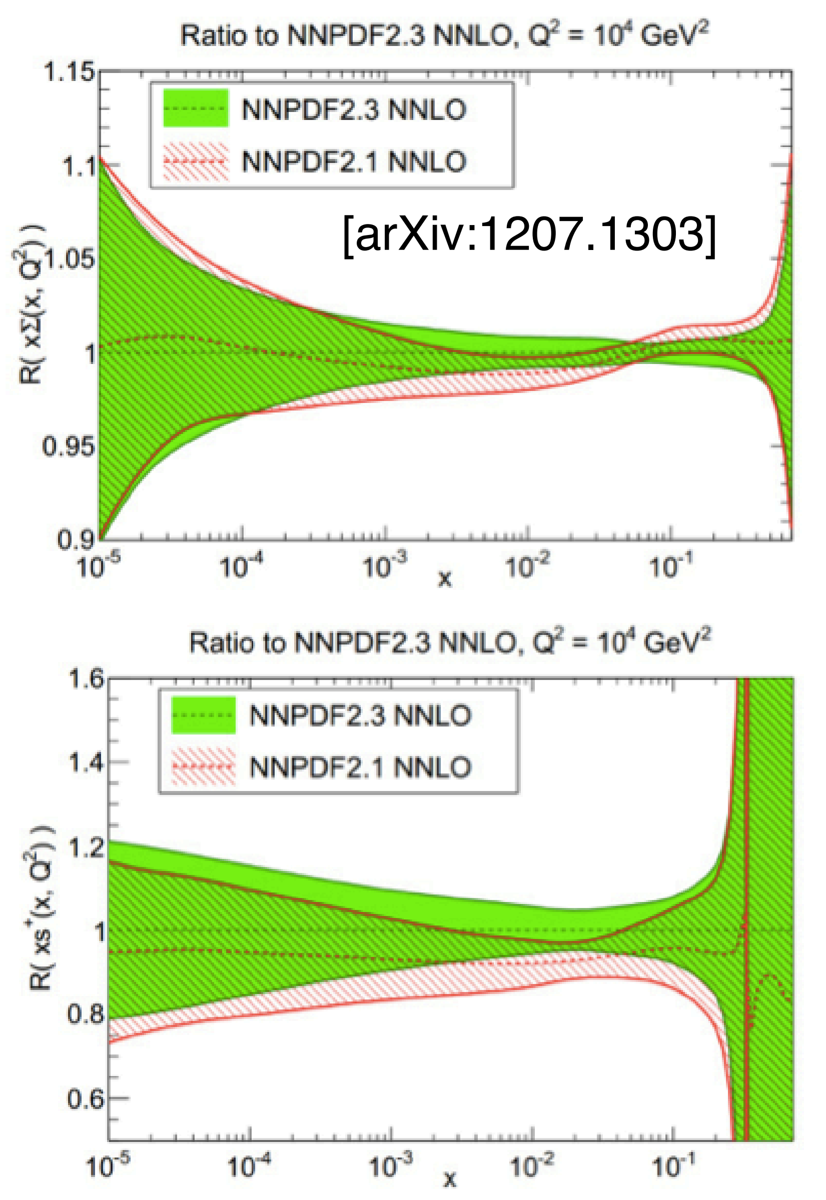
PDF progress

NNPDF2.3: First publicly available PDF set that includes LHC data in the fit.
Global fit, includes all relevant LHC data that were available with full covariance matrix

- ATLAS Inclusive Jets, 36pb^{-1}
- ATLAS W/Z lepton rapidity distributions, 36pb^{-1}
- CMS W lepton asymmetry, 840pb^{-1}
- LHCb W rapidity distributions, 36pb^{-1}

Impact of LHC data:

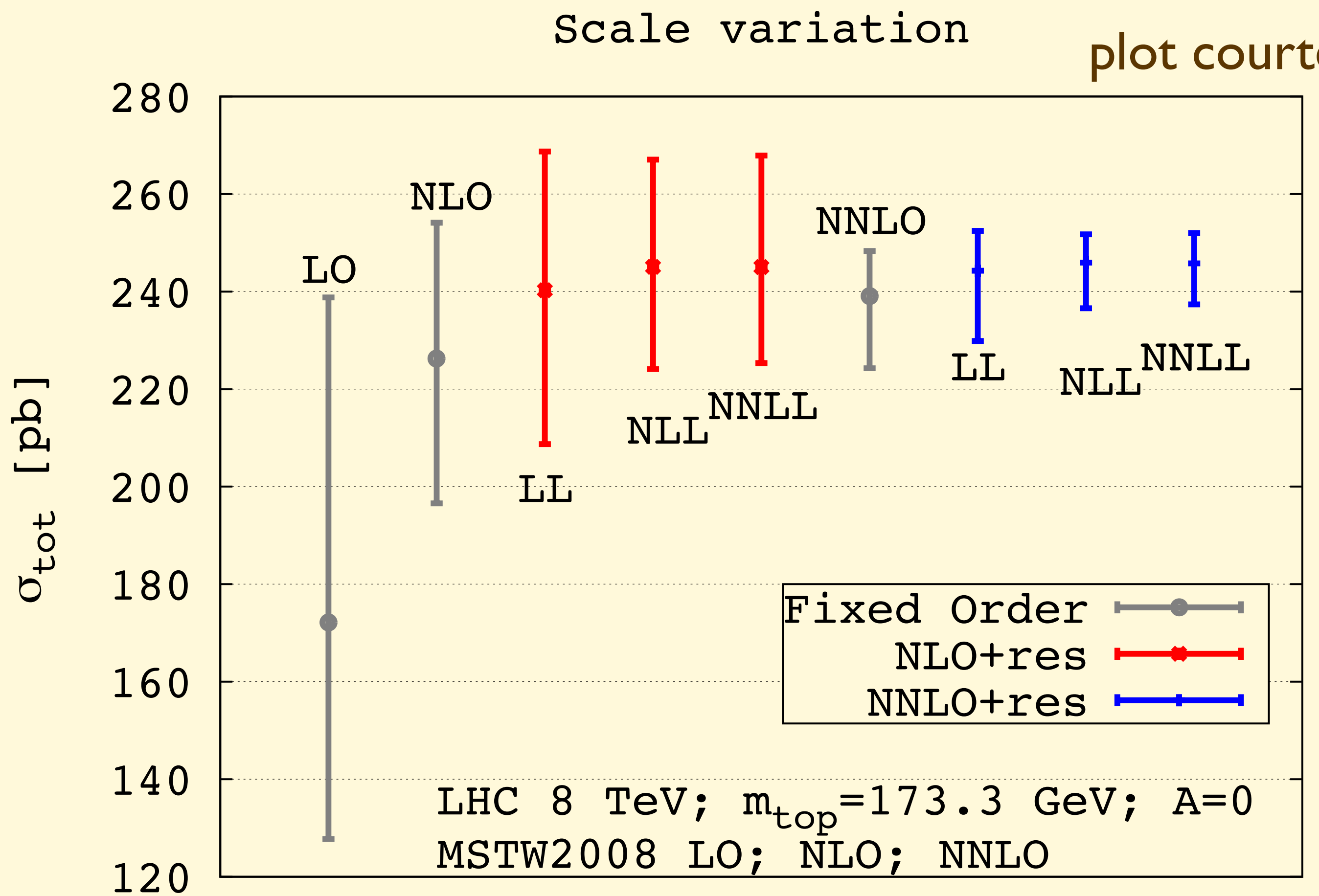
- Moderate effect from LHC data, generally less than half a sigma in central values.
- Largest impact is for Singlet and strange distributions.
- Expect more substantial improvements with 2011 and 2012 data.



Further progress from more data, and more accurate (NNLO) theory for a variety of processes probing different flavours and ranges of x and Q.

Inclusive tt cross section at NNLO

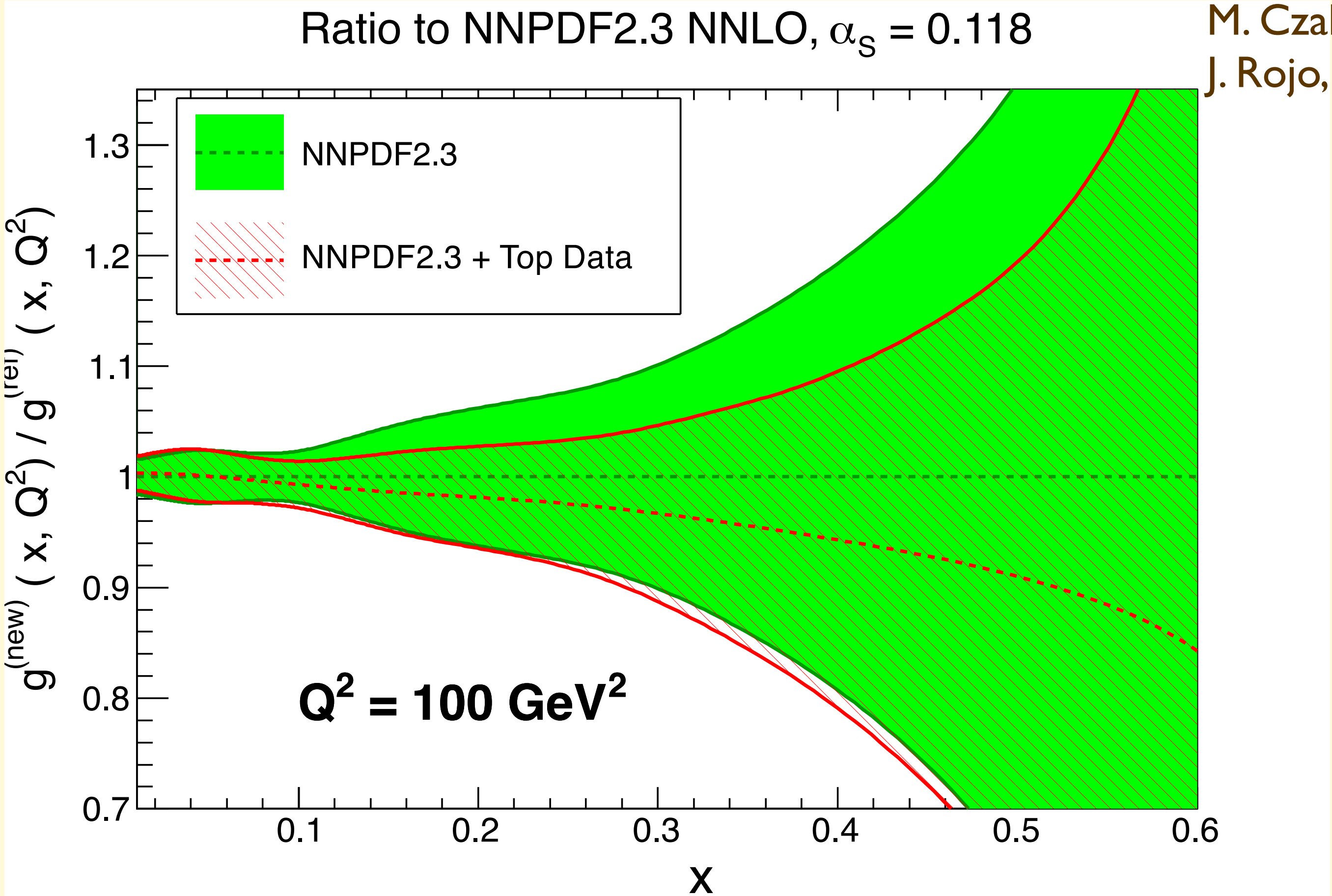
plot courtesy of A.Mitov



TH and parametric uncertainties are all of similar size:

- **Scale**: Independent μ_R , μ_F variation, ➡ 3%
  $0.5\ \mu_0 < \mu_{R,F} < 2\ \mu_0$ at $\mu_0 = m_{top}$,
  with $0.5 < \mu_R / \mu_F < 2$
- **PDF** (at 68%CL) ➡ 2-3%
- $\Delta\alpha_s = \pm 0.0007$ ➡ 1.5%
- $\Delta m_{top} = \pm 1$ GeV ➡ 3%

Constraining the gluon PDF with LHC σ(tt)

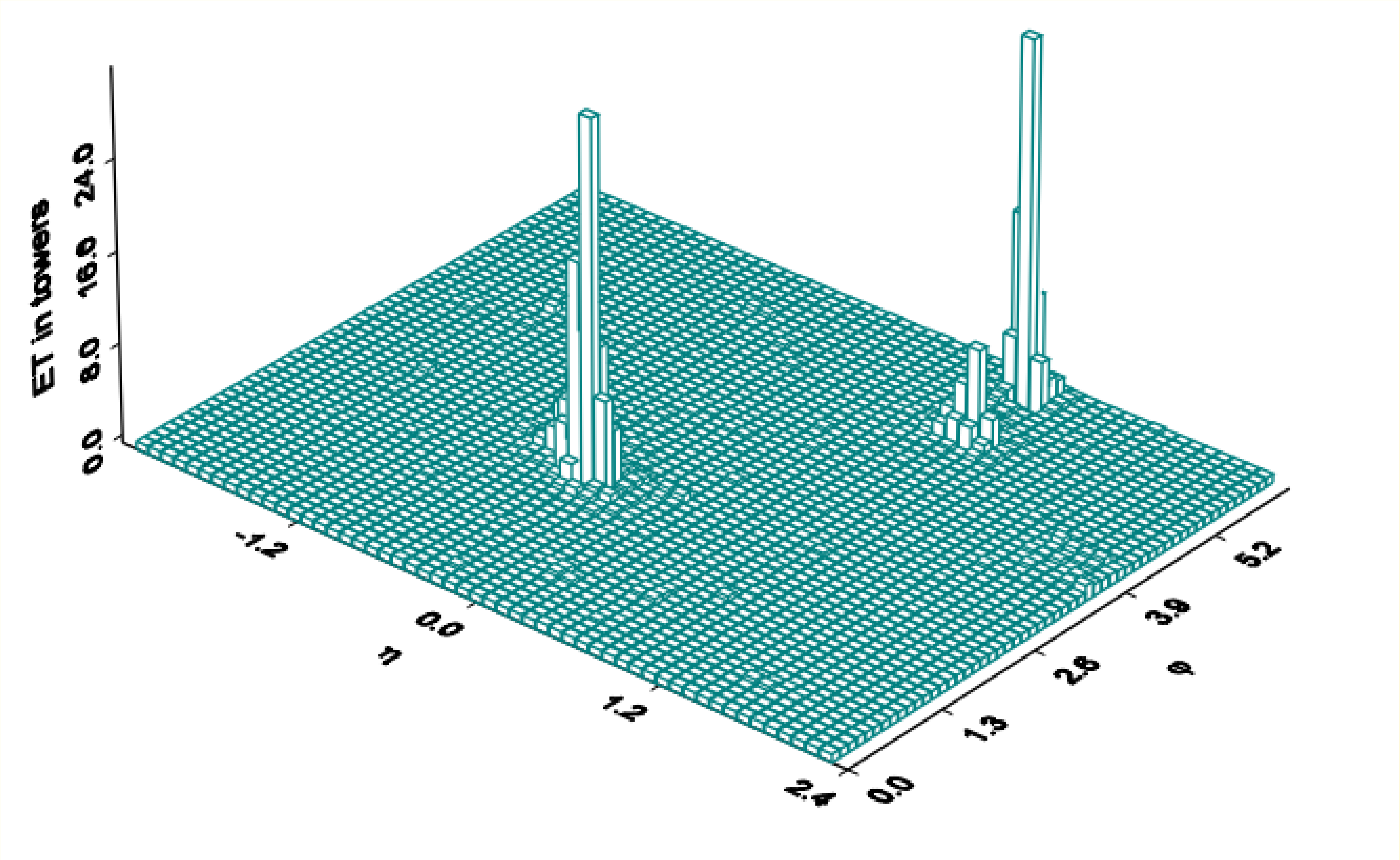


M. Czakon, MLM, A. Mitov, J. Rojo, arXiv:1303.7215

Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

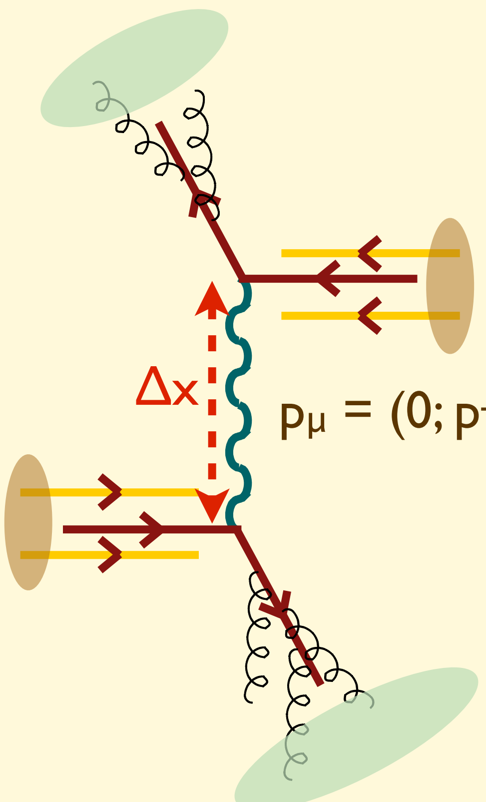
x-range relevant for gg→H is smaller. Direct probe: $d\sigma/dp_T$ (Z), to be calculated at NNLO

Jets in hadronic collisions



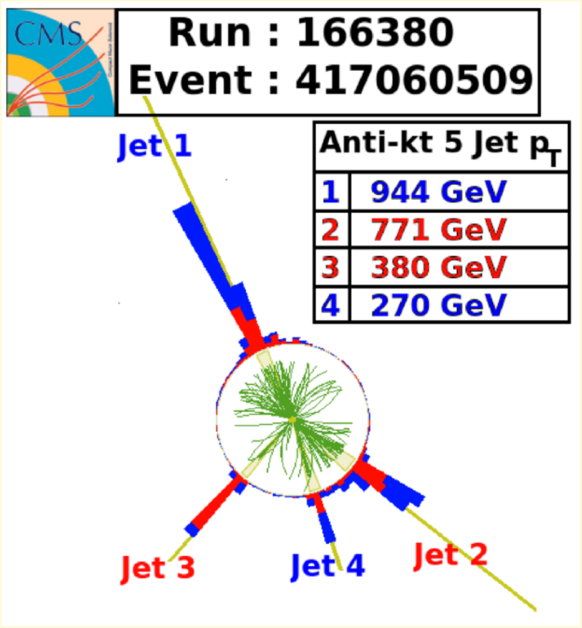
Jets

- Jet: focused stream of particles resulting from the evolution of a single accelerated quark or gluon
- Jet are used as probes of the quark structure (possible substructure implies departures from point-like behaviour of cross-section), or as probes of new particles (peaks in the invariant mass distribution of jet pairs)



$p_\mu = (0; p_T, 0, 0) \Rightarrow p^2 = -p_T^2$

In QM terms, $\Delta E = p_T$, and thus $\Delta t < 1/p_T$, and $\Delta x < 1/p_T$

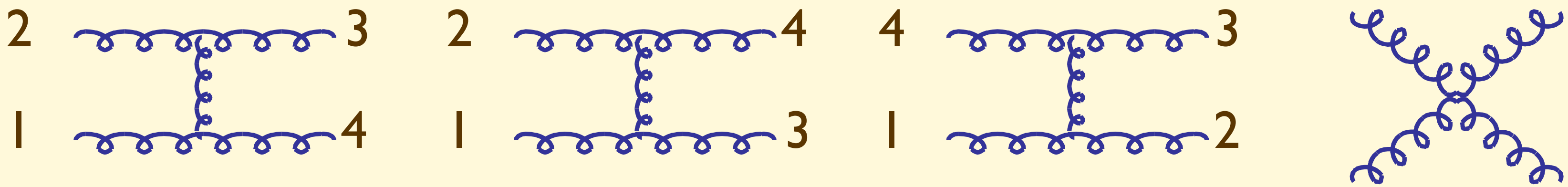


The most energetic jets observed at the LHC have $p_T \sim 2$ TeV

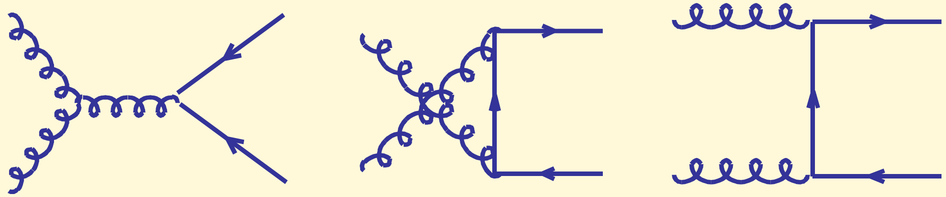
$\Rightarrow \Delta x \sim 10^{-4}$ of $R_{proton} \sim 10^{-17}$ cm ~ 1 nÅ $\sim 10^{18}$ GHz

- Inclusive production of jets is the largest component of high-Q phenomena in hadronic collisions
- QCD predictions are known up to NLO accuracy
- Intrinsic theoretical uncertainty (at NLO) is approximately 10%
- Uncertainty due to knowledge of parton densities varies from 5-10% (at low transverse momentum, p_T to 100% (at very high p_T, corresponding to high-x gluons)
- Jet are used as probes of the quark structure (possible substructure implies departures from point-like behaviour of cross-section), or as probes of new particles (peaks in the invariant mass distribution of jet pairs)

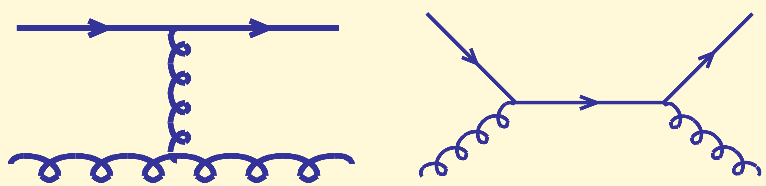
$gg \to gg$



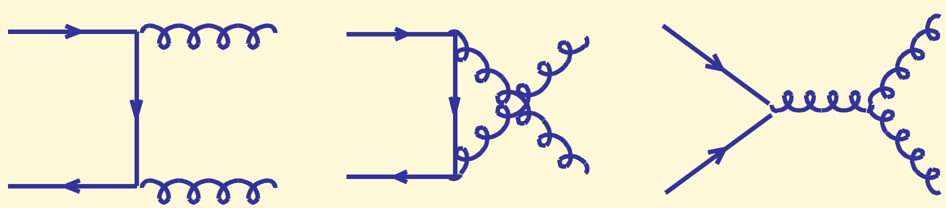
$gg \to q\bar{q}$



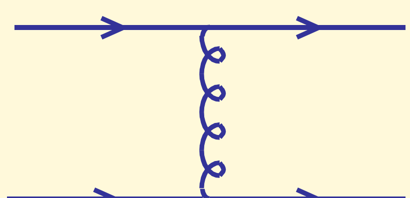
$qg \to qg$



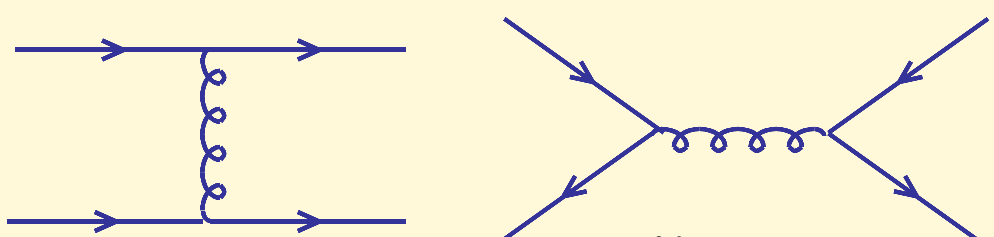
$q\bar{q} \to gg$



$qq' \to qq'$



$q\bar{q} \to q\bar{q}$



Phase space and cross-section for LO jet production

$$d[PS] = \frac{d^3 p_1}{(2\pi)^2 2p_1^0} \frac{d^3 p_2}{(2\pi)^2 2p_2^0} (2\pi)^4 \delta^4(P_{in} - P_{out})\, dx_1\, dx_2$$

(a) $$\delta(E_{in} - E_{out})\,\delta(P^z_{in} - P^z_{out})\, dx_1\, dx_2 = \frac{1}{2E^2_{beam}}$$

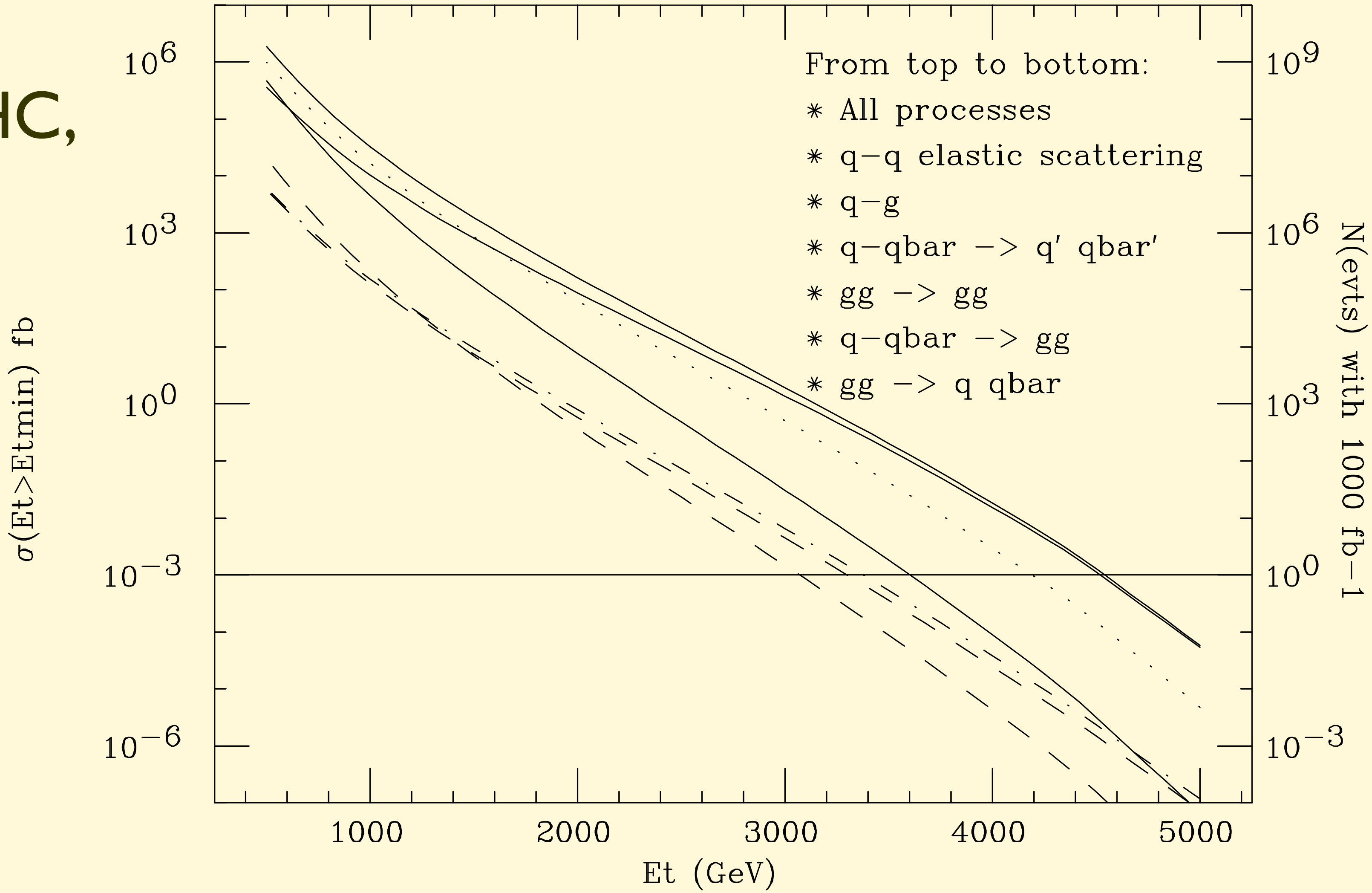
(b) $$\frac{dp^z}{p^0} = dy \equiv d\eta$$

$$d[PS] = \frac{1}{4\pi S} p_T\, dp_T\, d\eta_1\, d\eta_2$$

$$\frac{d^3\sigma}{dp_T d\eta_1 d\eta_2} = \frac{p_T}{4\pi S} \sum_{i,j} f_i(x_1)\, f_j(x_2) \frac{1}{2\hat{s}} \overline{\sum_{kl}} |M(ij \to kl)|^2$$

The measurement of pT and rapidities for a dijet final state uniquely determines the parton momenta x_1 and x_2. Knowledge of the partonic cross-section allows therefore the determination of partonic densities f(x)

Jet production rates at the LHC, subprocess composition



The presence of a quark substructure would manifest itself via contact interactions (as in Fermi's theory of weak interactions). On one side these new interactions would lead to an increase in cross-section, on the other they would affect the jets' angular distributions. In the dijet CMF, QCD implies Rutherford law, and extra point-like interactions can then be isolated using a fit. With the anticipated statistics of 300 fb-1, limits on the scale of the new interactions in excess of 40 TeV should be reached (to increase to 60 TeV with 3000 fb-1)

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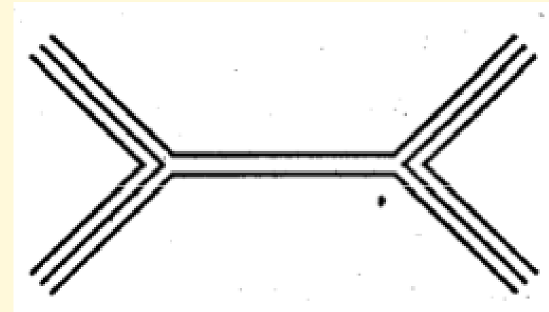


From the supercollider-bible of the 80's,

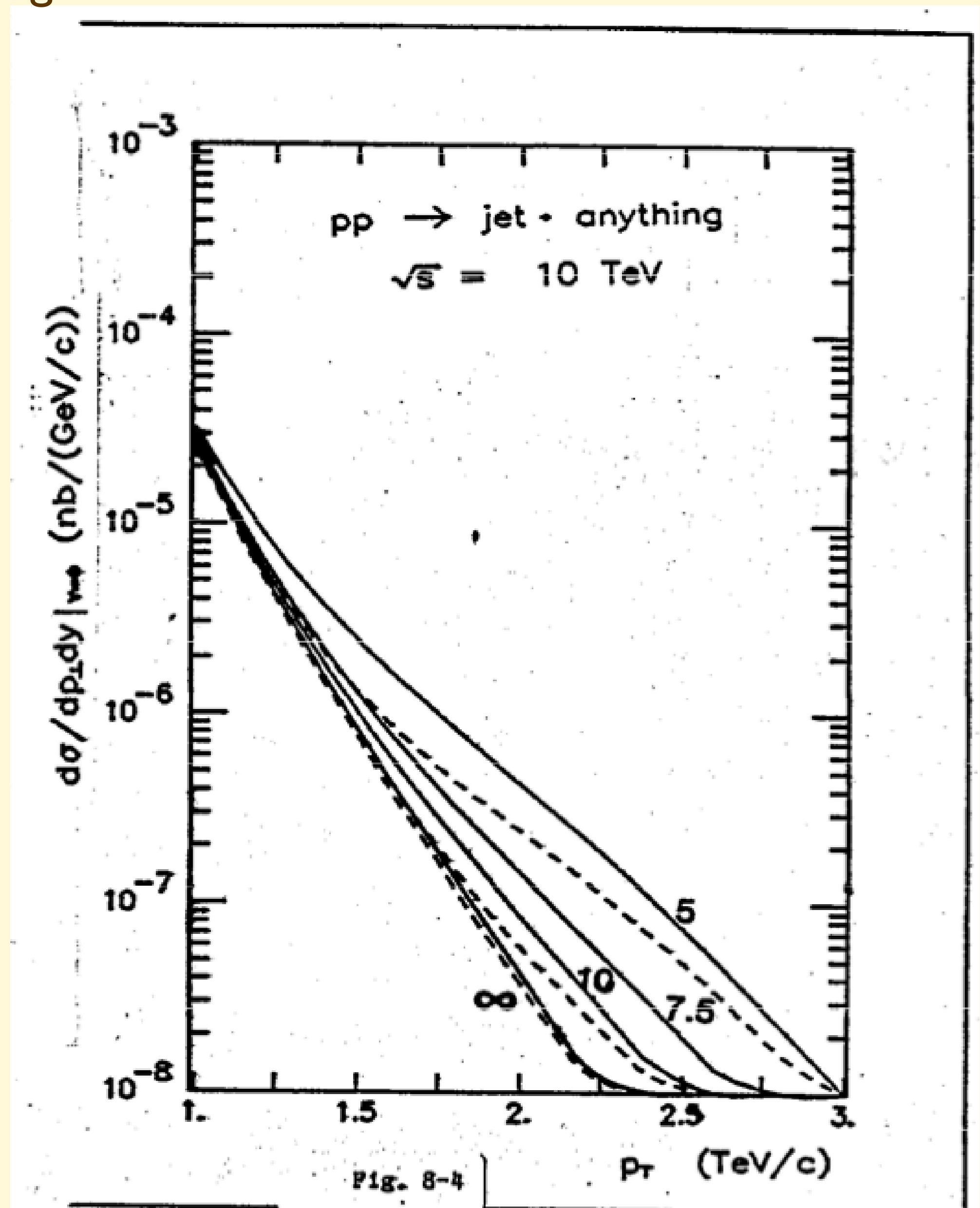
EHLQ (Eichten, Hinchliffe, Lane, Quigg): "Supercollider Physics",

Rev.Mod.Phys. 56 (1984) 579-707

$$|A(u\bar{u}\to u\bar{u})|^2 = |A(d\bar{d}\to d\bar{d})|^2 =$$

$$\frac{4}{9}\alpha_s^2(Q^2)\left[\frac{(\hat{u}^2+\hat{s}^2)}{\hat{t}^2} + \frac{(\hat{u}^2+\hat{t}^2)}{\hat{s}^2} - \frac{2}{3}\cdot\frac{\hat{u}^2}{\hat{s}\hat{t}}\right]$$

$$+\frac{8}{9}\alpha_s(Q^2)\frac{\eta_0}{\Lambda^{*2}}\left(\frac{\hat{u}^2}{\hat{t}}+\frac{\hat{u}^2}{\hat{s}}\right) + \frac{8}{3}\left(\frac{\eta_0\hat{u}}{\Lambda^{*2}}\right)^2;$$

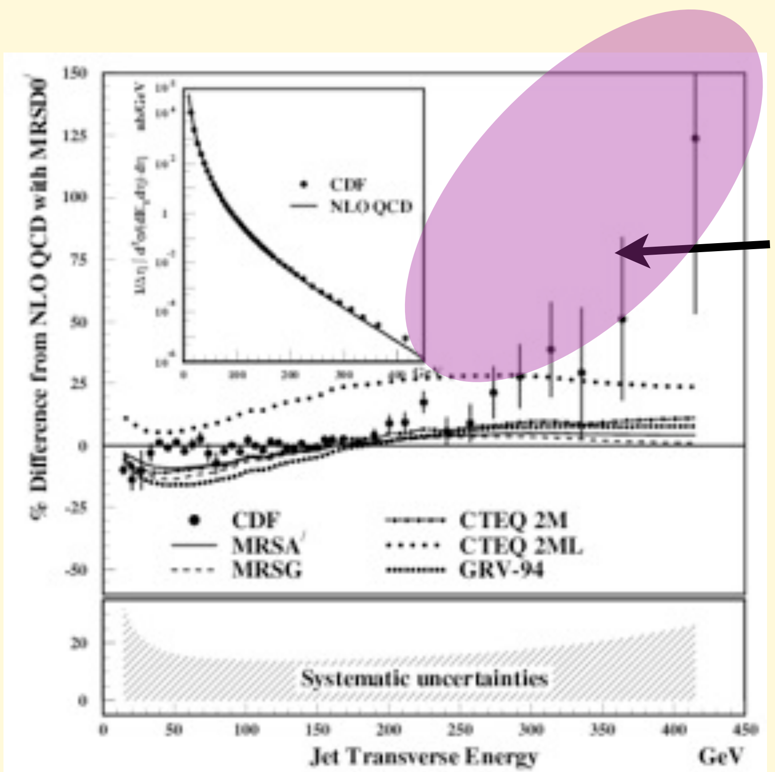


At the LHC, with the anticipated statistics of 300 fb-1, limits on the scale of the new interactions in excess of 40 TeV should be reached (to increase to 60 TeV with 3000 fb-1)

Possible surprises from jet physics, an example from the past (1995)

Analysis of large-ET jet production at the Tevatron

[QCD_{NLO} / data – 1] (%)

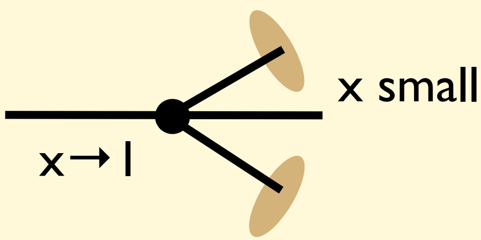


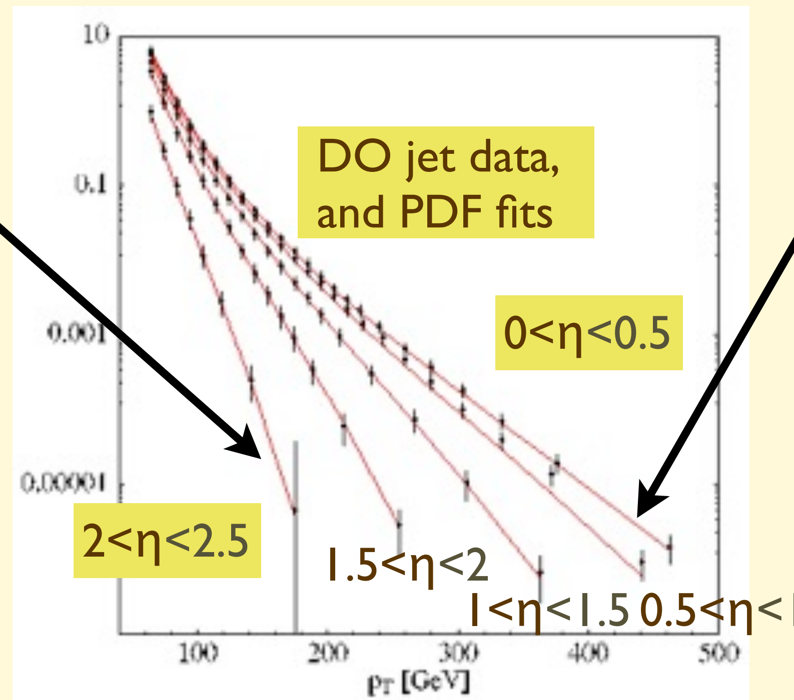
Large excess ⇒ **quark substructure** ??

Effect later understood as poor knowledge/ parameterization of the gluon density of the proton at x→1, using asymmetric, low-ET final states:

Control region

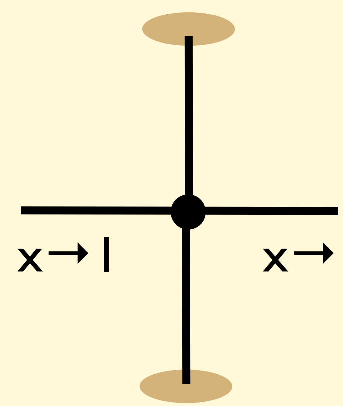
fwd jets - low ET, small √s, no BSM "contamination", extract large-x PDF



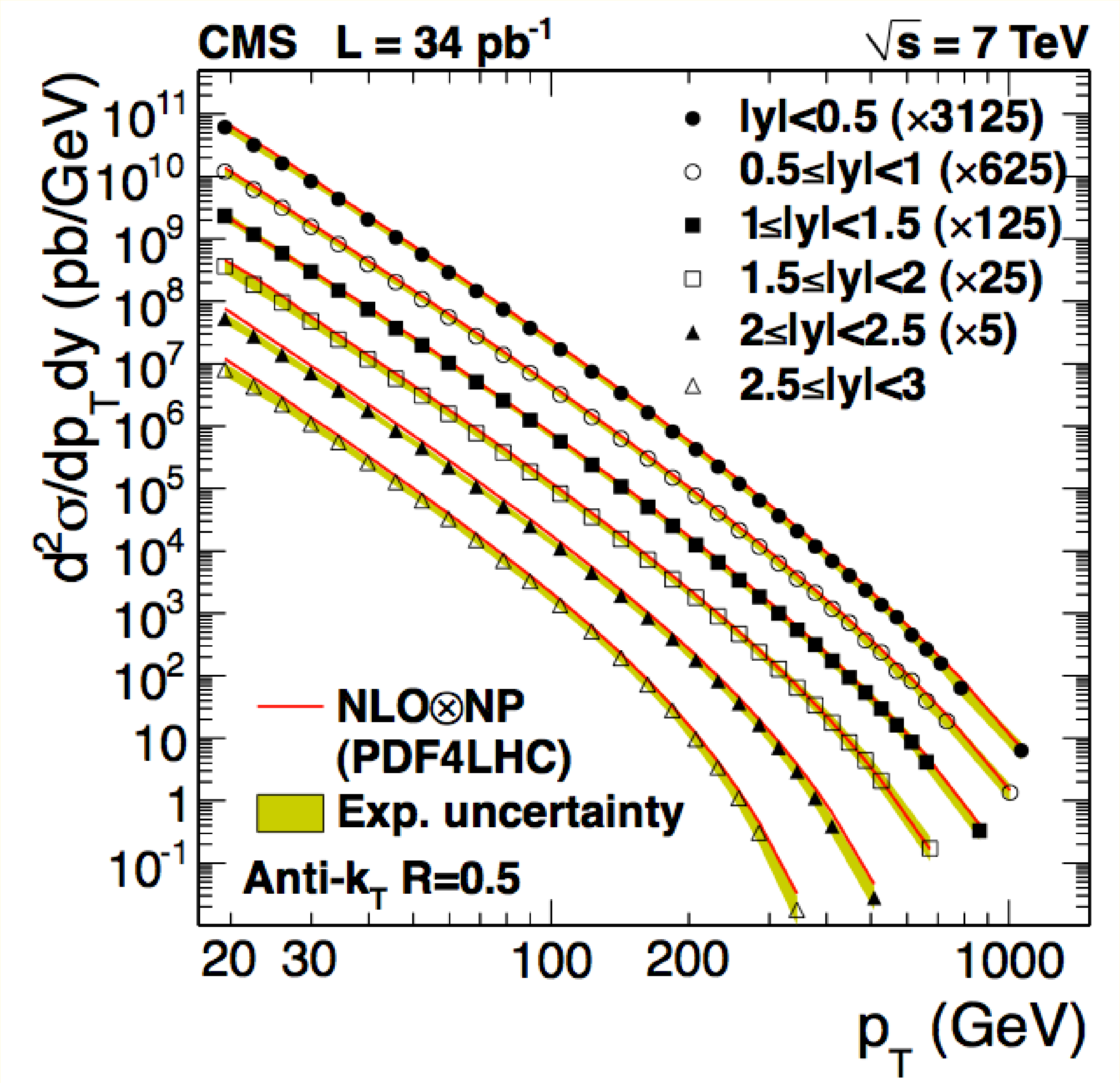


Signal region

central jets - high ET, large √s, explore quark substructure



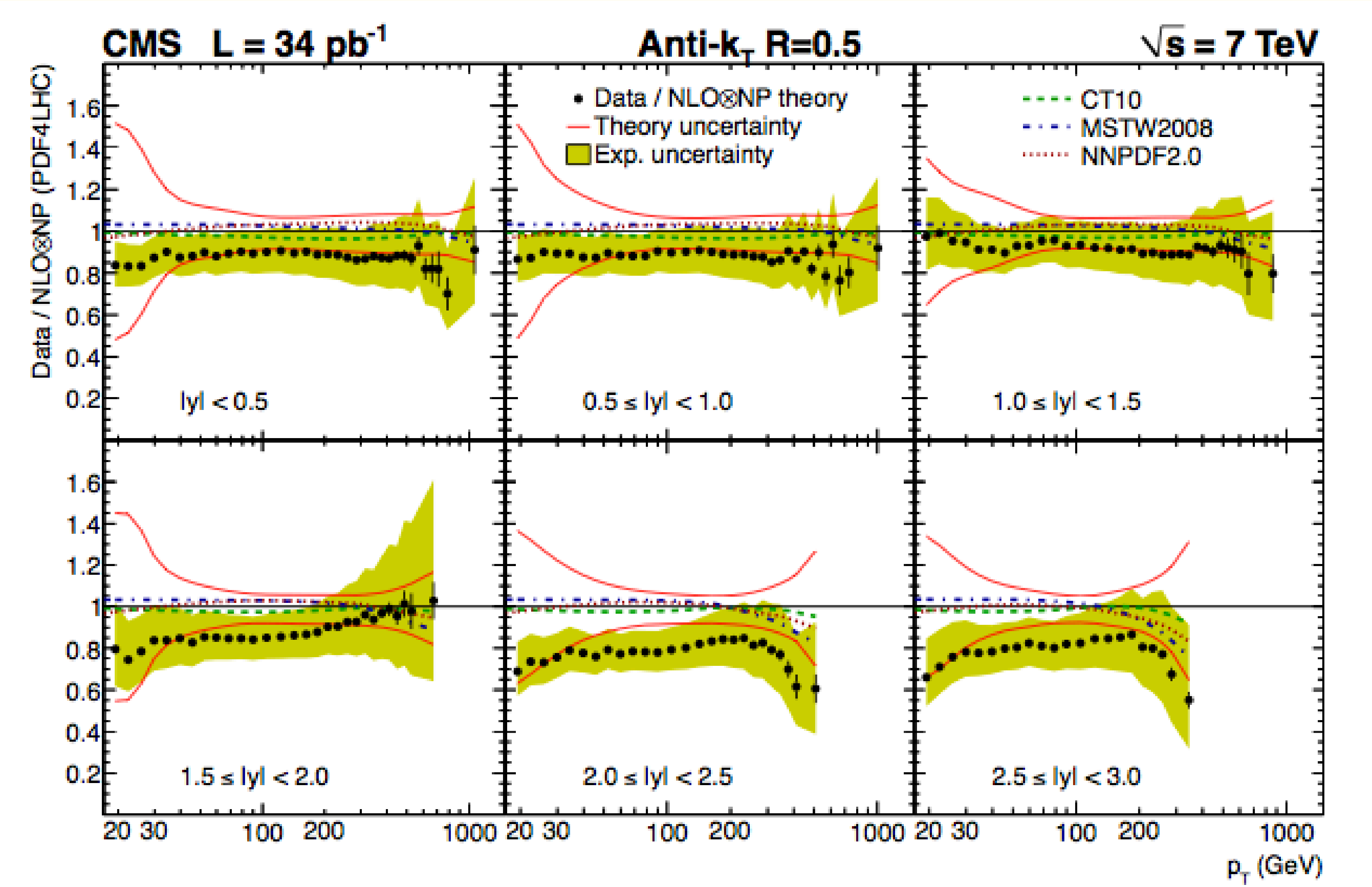
Jet production at the LHC, data vs TH



Rates span 10 orders of magnitude!

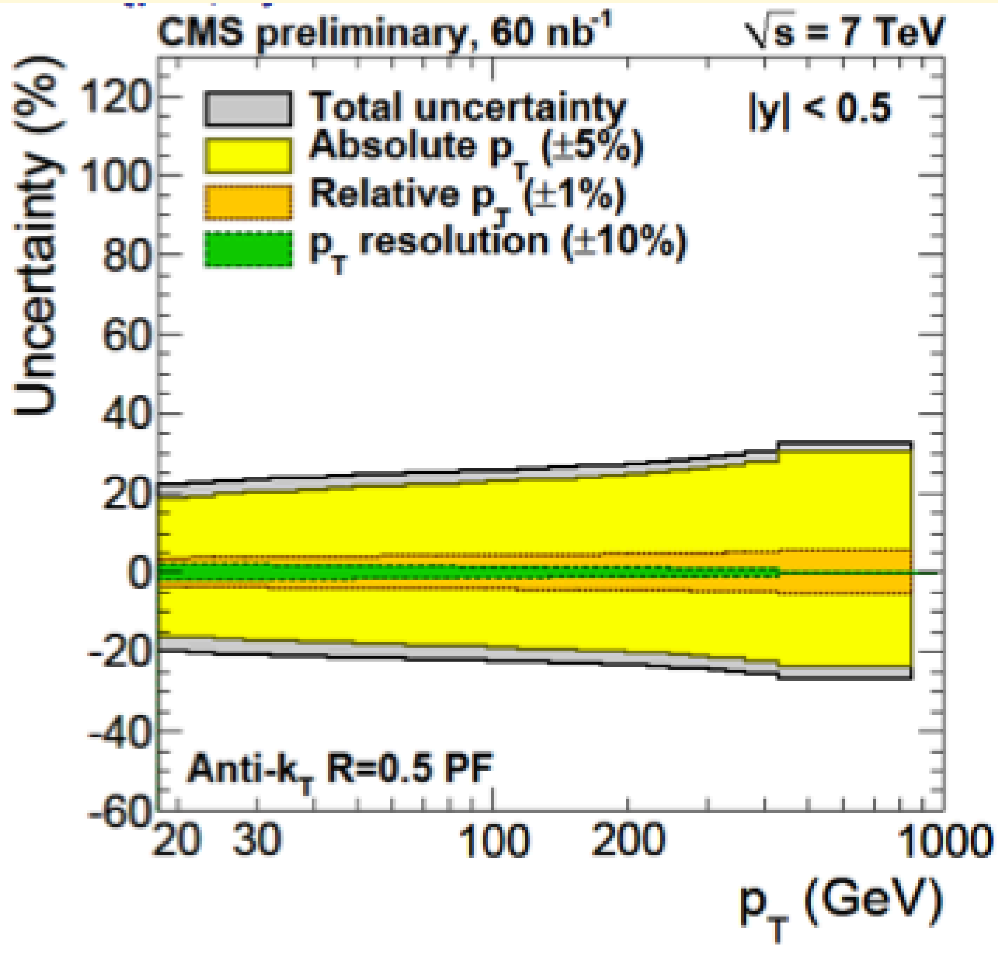
Jet cross section: data vs NLO

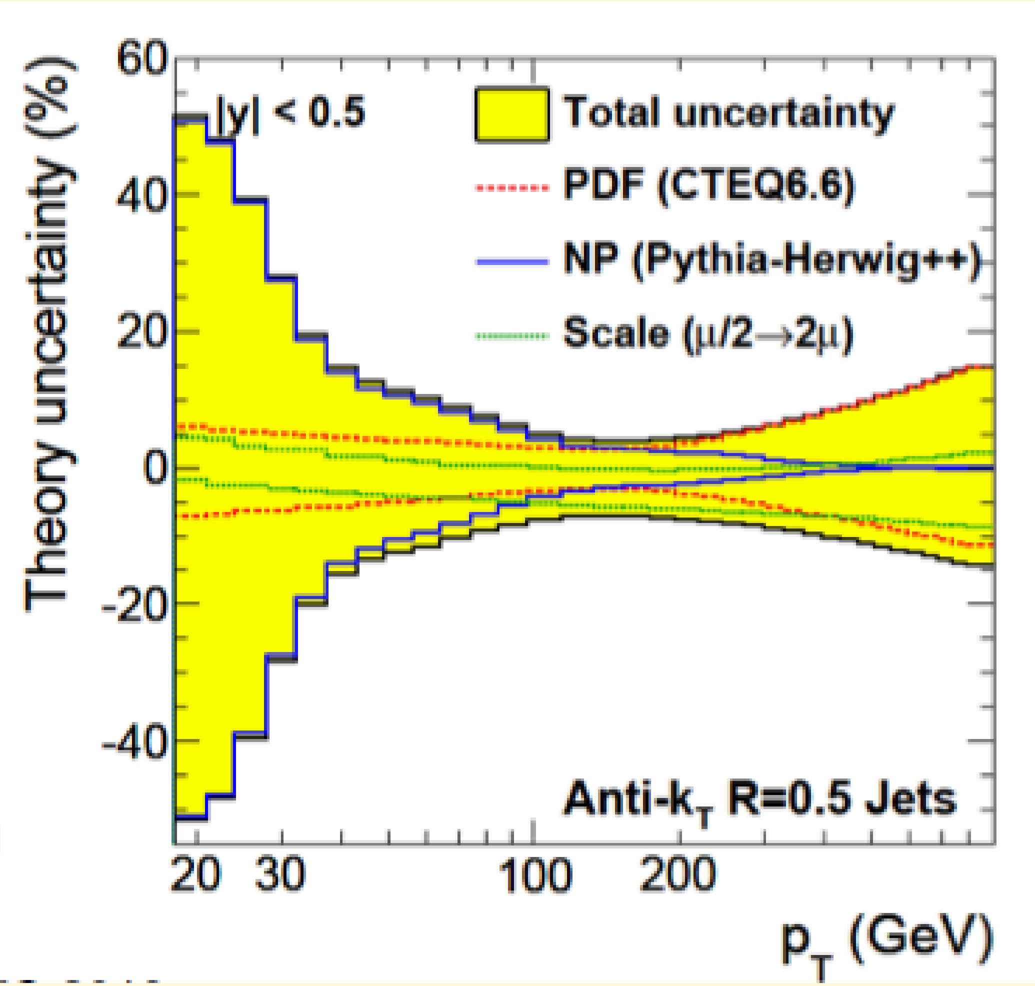
Theory: absolute prediction for both shape and normalization



Agreement to within 20% (over 10 orders of magnitude!)

Residual discrepancy consistent with PDF and perturbative NLO uncertainties

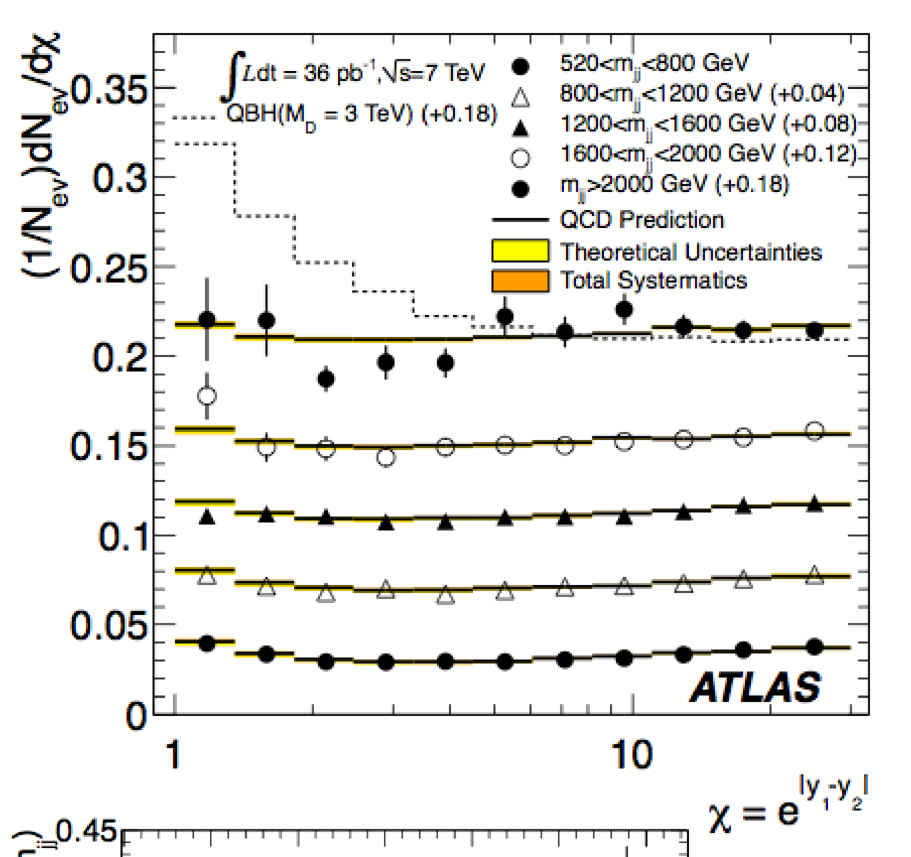


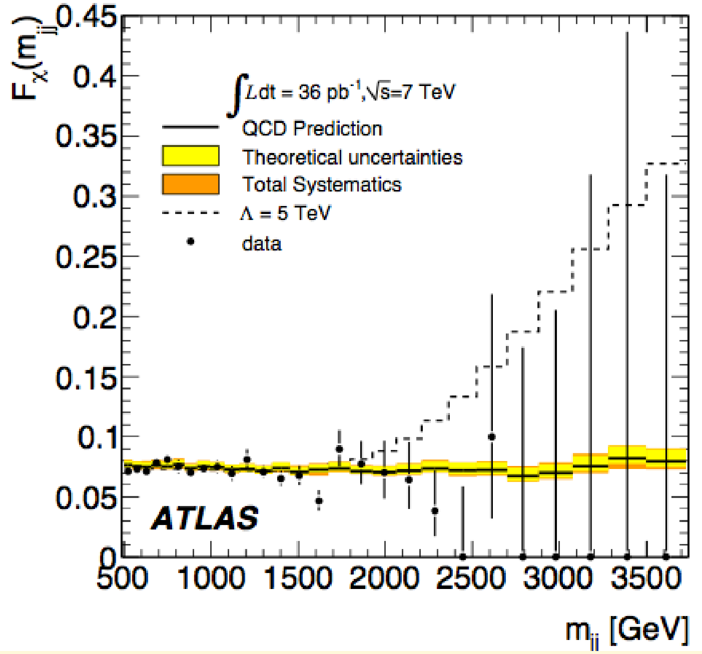


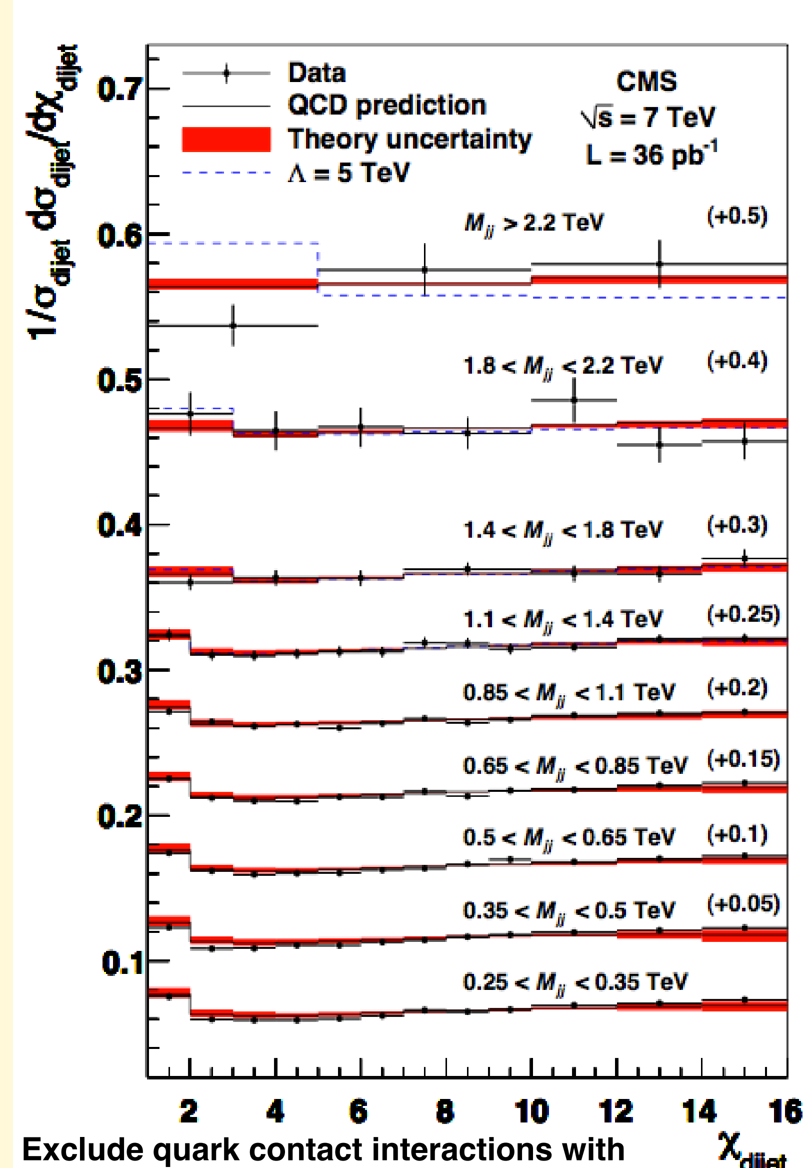
PDF will be dominant source of theoretical systematics at large E_T

Constraints on quark contact interactions

$$\chi = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$





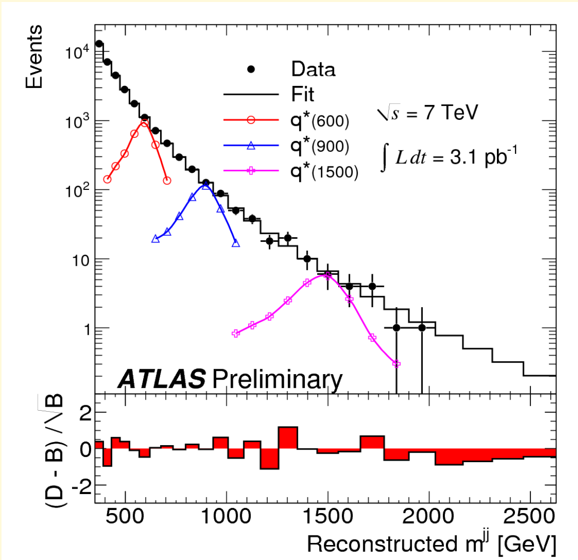


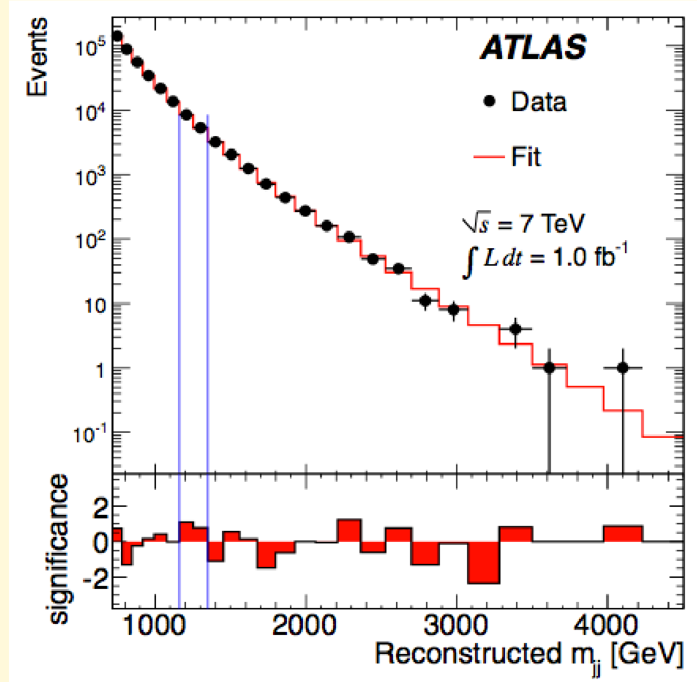
Exclude quark contact interactions with scale < 5 TeV @ 95% CL

Quarks appear pointlike even at the distances probed by the LHC

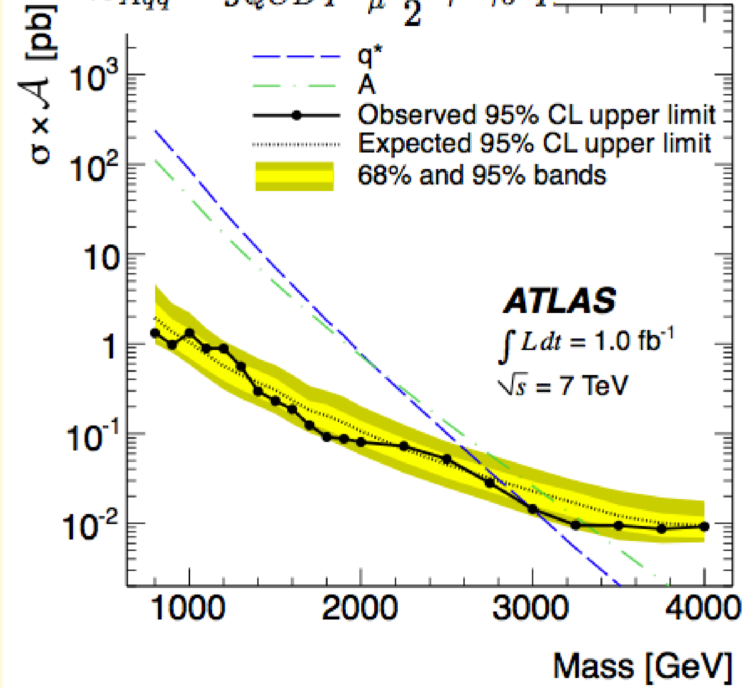
Dijet resonance searches

ATLAS: arXiv:1108.6311

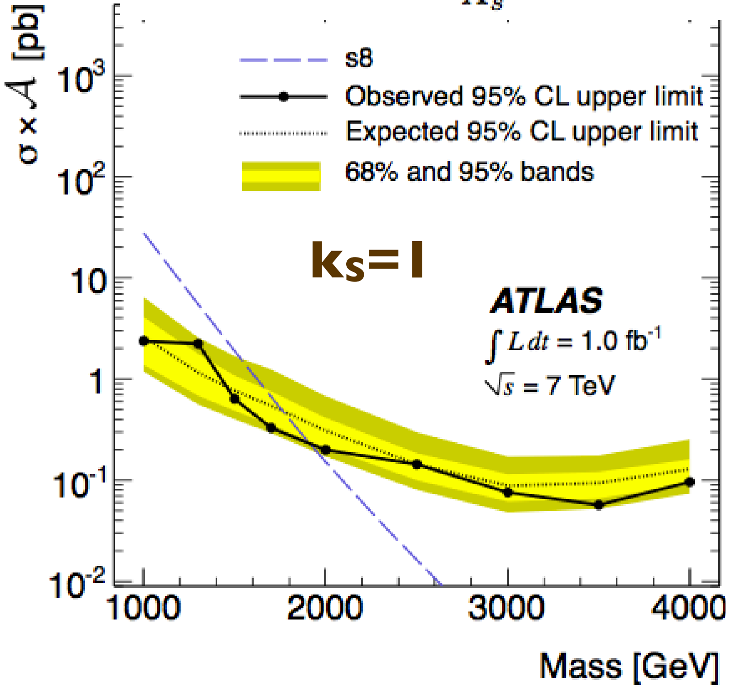




$$\mathcal{L}_{Aq\bar{q}} = g_{QCD}\bar{q}A^a_\mu \frac{\lambda^a}{2}\gamma^\mu\gamma_5\, q$$



$$\mathcal{L}_{gg8} = g_{QCD}d^{ABC}\frac{\kappa_s}{\Lambda_s}S^A_8 F^B_{\mu\nu}F^{C,\mu\nu}$$



No evidence for forces acting on quarks in addition to the SM ones

Model	95% CL Limits (TeV)	
	Expected	Observed
Excited Quark q^*	2.81	2.99
Axigluon	3.07	3.32
Colour Octet Scalar	1.77	1.92

A useful ref:

Hard Interactions of Quarks and Gluons: a Primer for LHC Physics

http://arXiv.org/abs/hep-ph/0611148