ISR (q/g) for New physics

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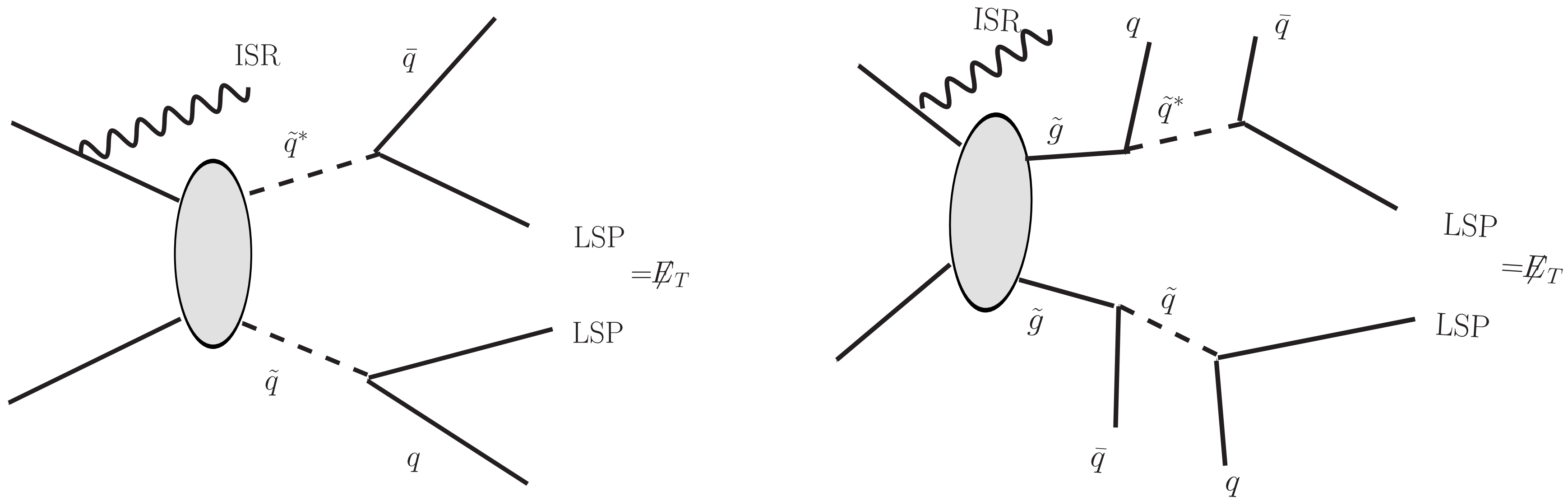
This talk.

- Motivation of using ISR.
- Basic properties of ISR, quark and gluon cases.
- ISR tagging.
- More applications.

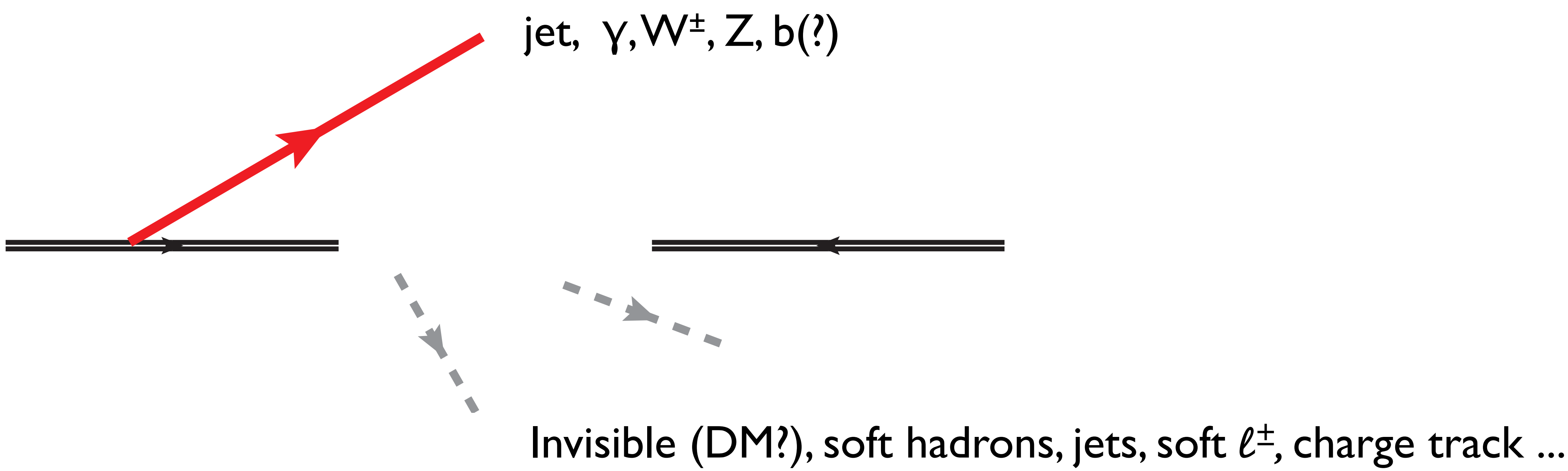
Relatively new field.
I will focus on qualitative features.
Hope to encourage further study.

Why ISR

- Always there.
  - Many NP candidates are colored. Production dominated by QCD production.
  - ISR significant, similar to ttbar.
  - Identifying them help characterizing the signal.



Must use ISR: compressed spectrum

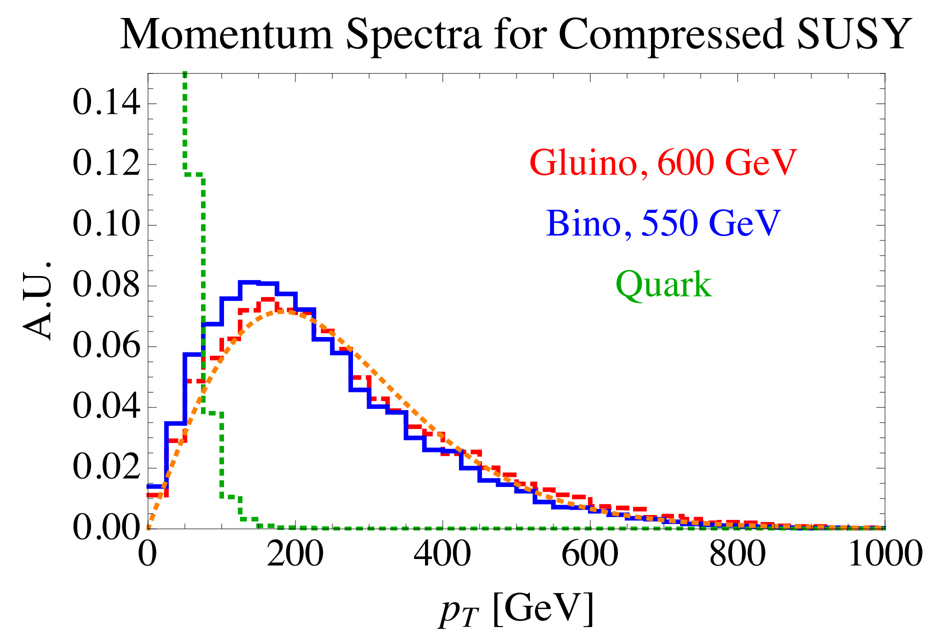


- ISR + soft jet ...
  - More challenging signal, could be the reason that we have not discover them yet.

Limitation in sensitivity

- MET ∝ $E_{visible}$

$$\tilde{g} \to q\bar{q}\tilde{B}.$$



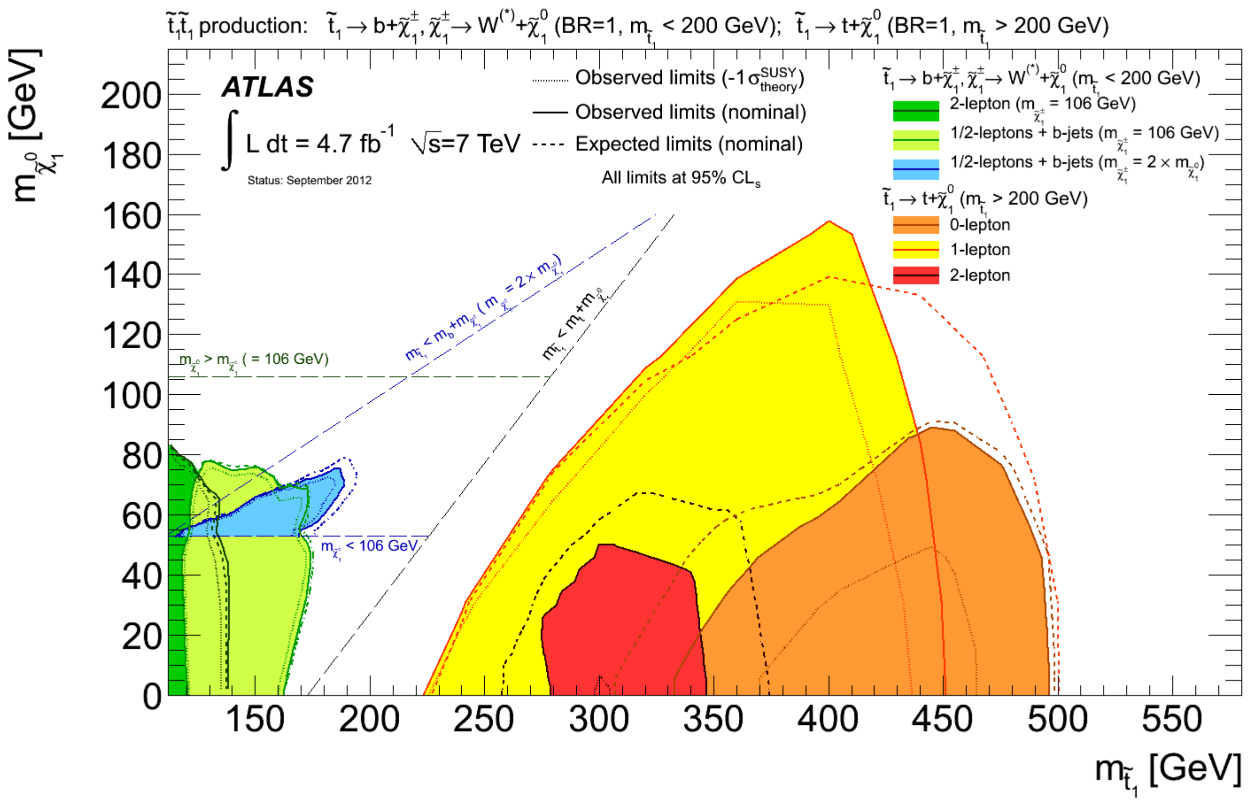
- Sensitivity limited with traditional SUSY searches.

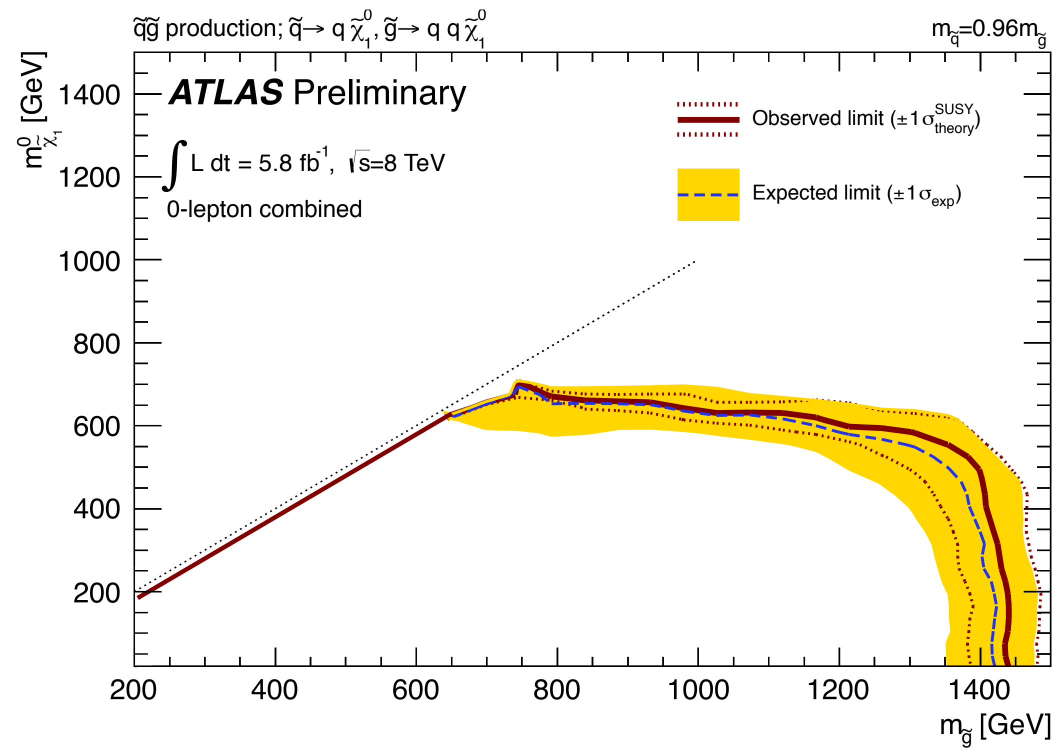
- Another important example

$$\tilde{t} \to t + \chi^0$$

$$m_{\tilde{t}} - m_{\mathrm{LSP}} \sim m_t$$ Signal kinematics very similar to SM ttbar

Closing gaps using ISR?

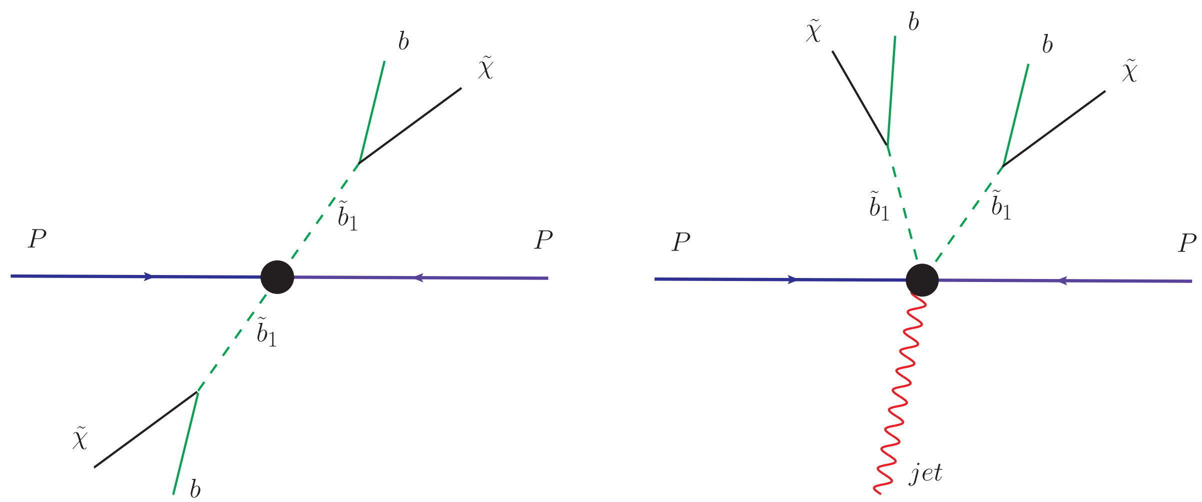


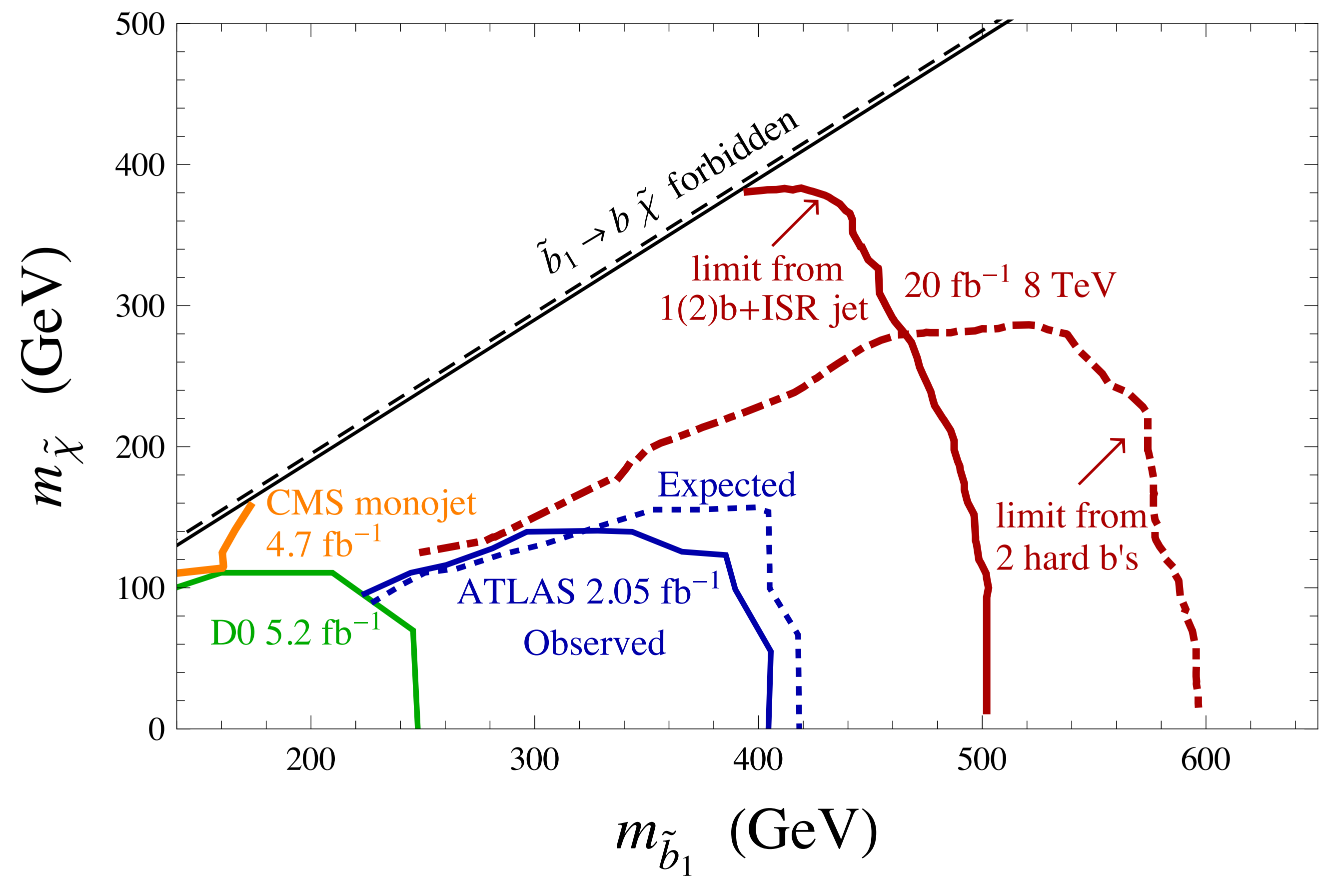


- Won't be easy.
- At least it is one additional handle.

Closing the gap in sbottom search

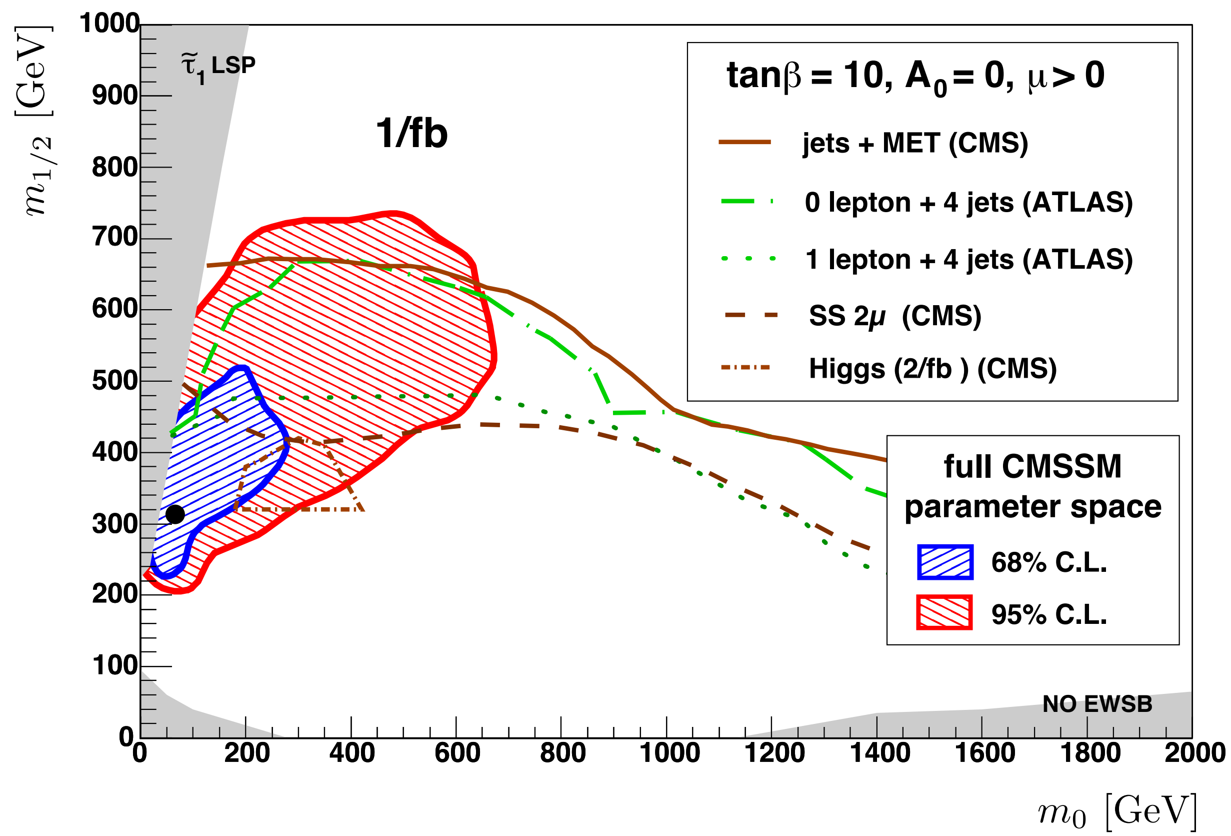
Bai, Alvarez, 1204.5182





More motivation: dark matter

- $\Omega_{SUSY\_LSP} = \Omega_{obs} \Rightarrow$ compressed spectrum.
  - "vanilla" SUSY can be off by 10^2
- Coannhilation: $M_{NLSP} - M_{LSP} \sim 5\% \, M_{LSP}$

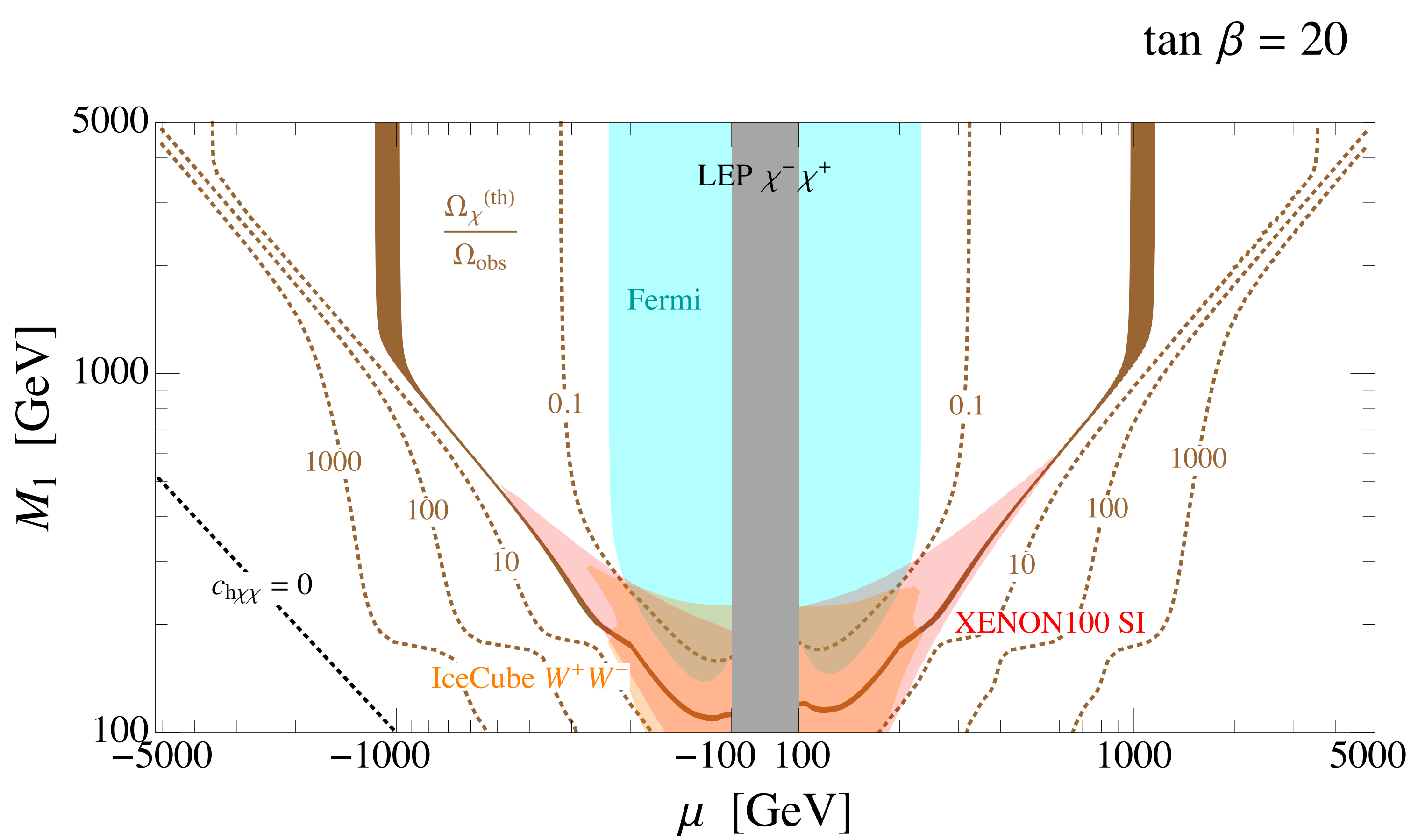


squark-neutralino, gluino-neutralino... coannhilation also possible in more general models

More (dark) motivations.

- Well tempered (giving correct Ω_{obs}).
  - Efficient annihilation ⇒ small mass splitting

N. Arkani-Hamed, A. Delgado, G. Giudice, hep-ph/0601041



Cheung, Hall, Ruderman, 1211.4873

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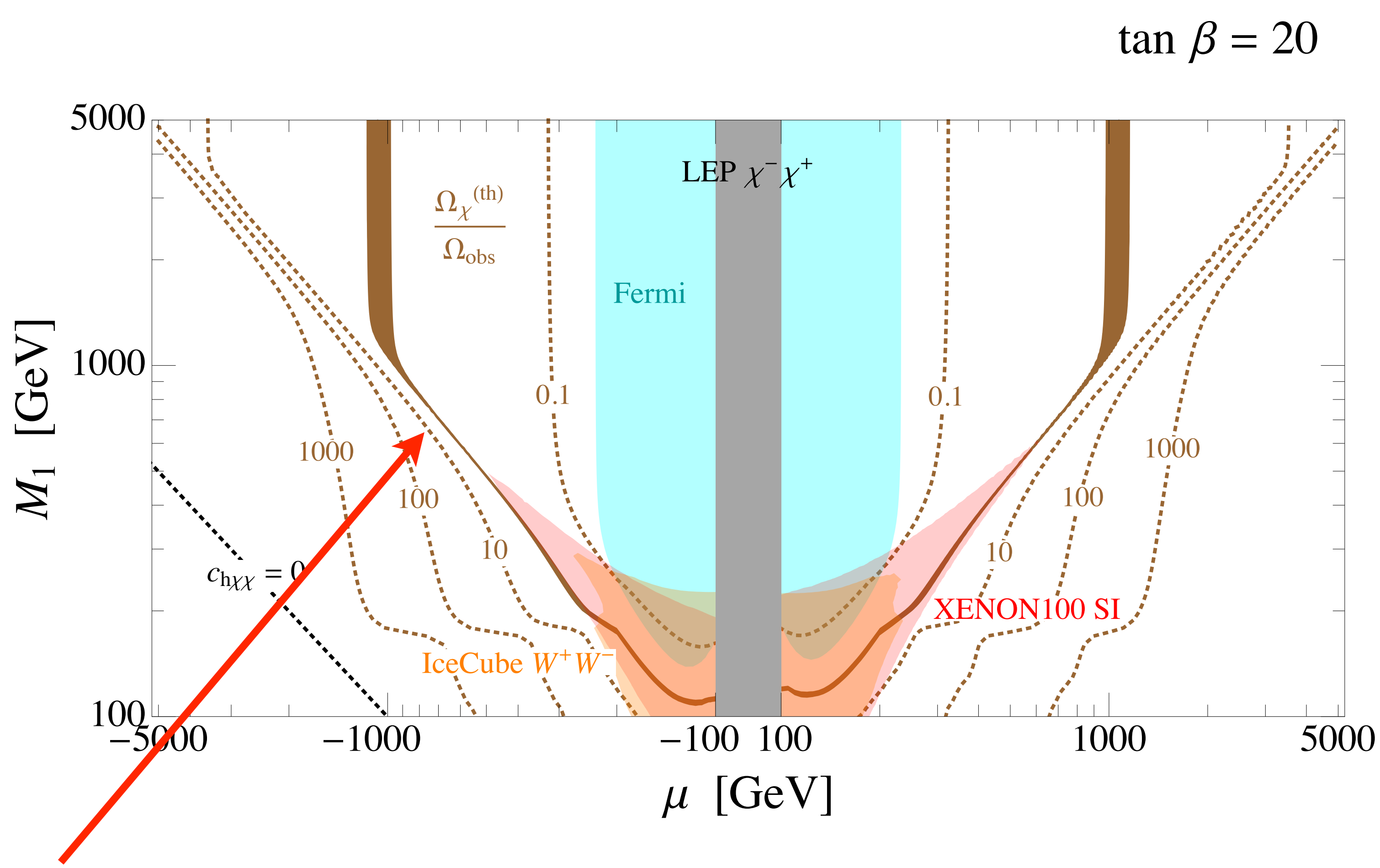


Cheung, Hall, Ruderman, 1211.4873

small mass splitting

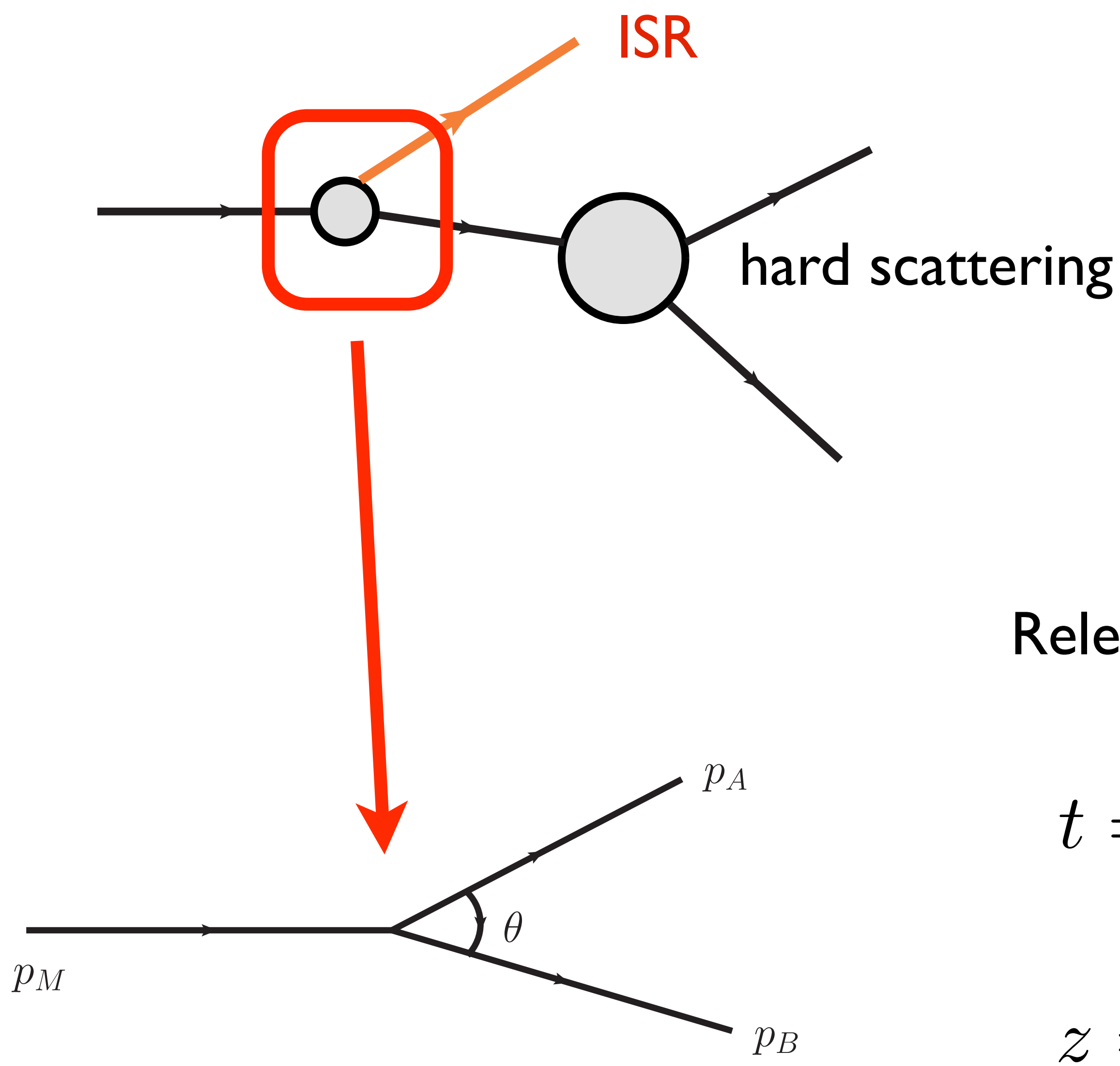
More motivations.

- Just (light) wino or Higgsino.
  - $SU(2)_L$ ⇒ (Very) compressed, ~GeV or less mass gap between chargino and neutralino.
  - For example, anomaly mediation.
- Low scale SUSY breaking which feeds universally to all superpartners.
  - "Compact SUSY"

Nomura, Murayama, Shirai, Toboika, 1206.4993

Qualitative feature of ISR

Parton splitting, collinear limit



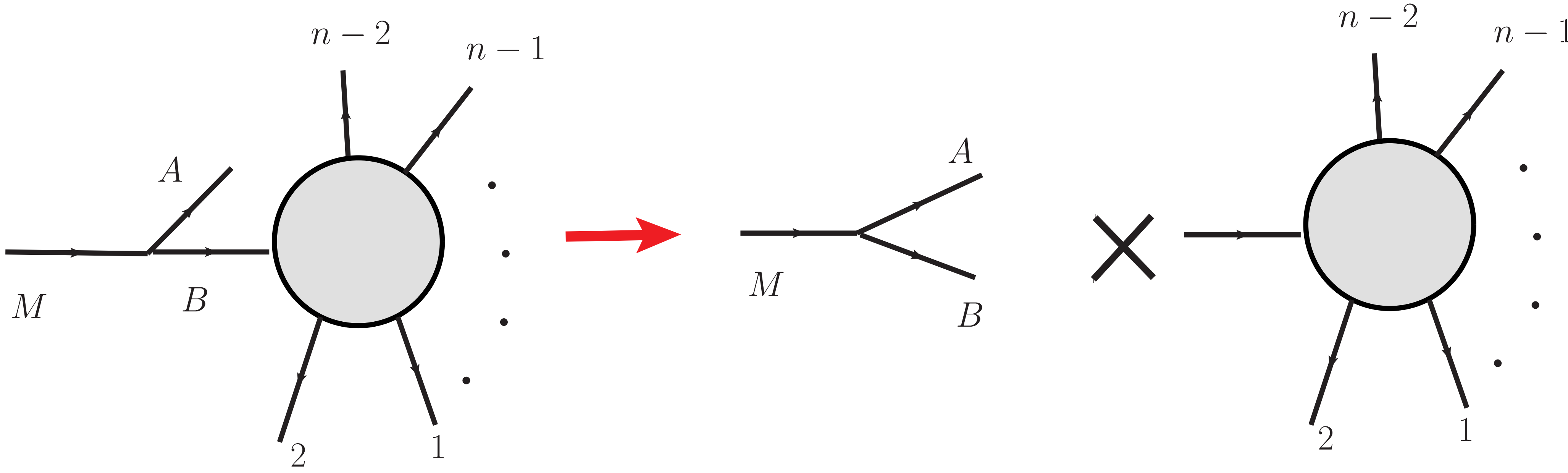
Relevant kinematical variables

$$t = |p_B^2| = |(p_M - p_A)^2|$$

$$z = \frac{E_A}{E_M} \qquad \phi$$

$$\frac{dt}{t} = \frac{d\theta^2}{\theta^2} = \frac{dp_T^2}{p_T^2}$$

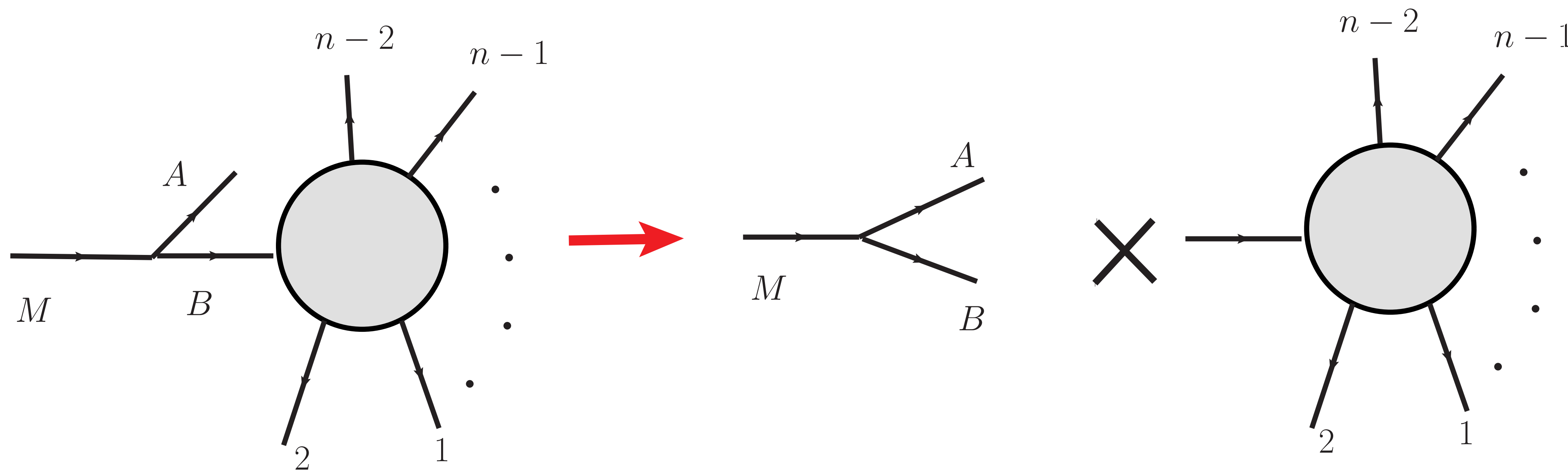
Collinear limit



$|\mathcal{M}_{n+1}|^2 = |\mathcal{M}(p_1,...p_A,p_B)|^2$ $\quad$ $|\mathcal{M}_n(p_1,...p_M)|^2$ $\quad \times \quad$ $|\mathcal{M}(p_M \to p_A p_B)|^2$

$$|\mathcal{M}_{n+1}|^2 d\Pi_{n+1} \simeq |\mathcal{M}_n|^2 d\Pi_n \frac{dt}{t}\frac{\alpha_S}{2\pi}P(z)dzd\phi$$

Collinear limit



$|\mathcal{M}_{n+1}|^2 = |\mathcal{M}(p_1,...p_A,p_B)|^2 \qquad |\mathcal{M}_n(p_1,...p_M)|^2 \quad \times \quad |\mathcal{M}(p_M \to p_A p_B)|^2$

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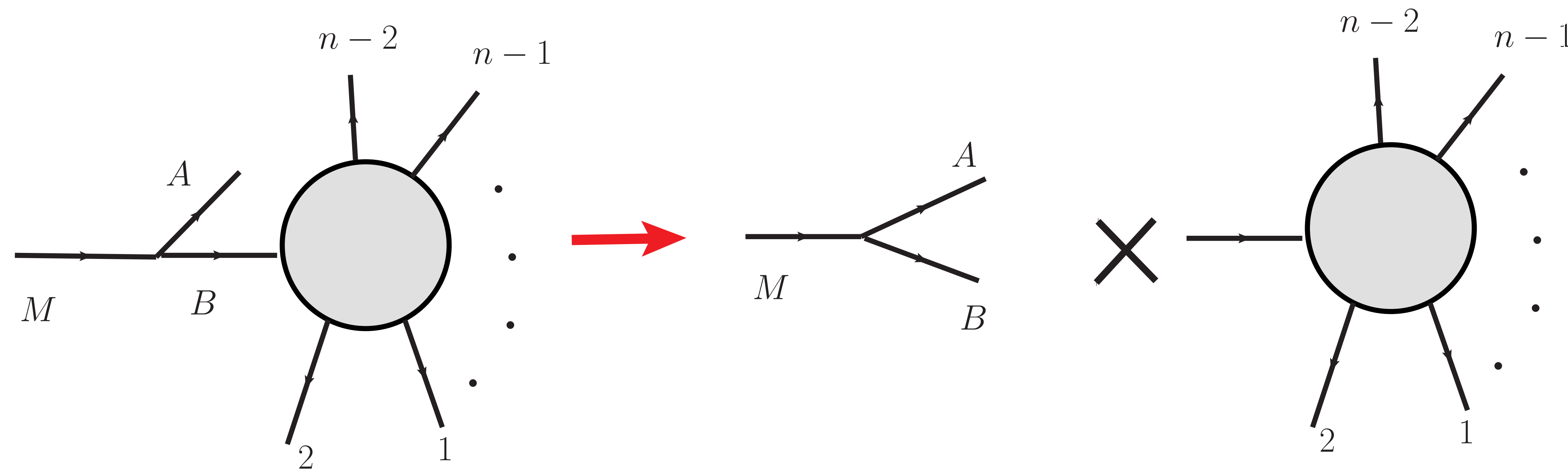
collinear singularity: t⇒0

$$\frac{dt}{t} = \frac{d\theta^2}{\theta^2} = \frac{dp_T^2}{p_T^2}$$

Collinear limit



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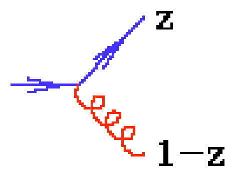
collinear singularity: t⇒0

$$\frac{dt}{t} = \frac{d\theta^2}{\theta^2} = \frac{dp_T^2}{p_T^2}$$

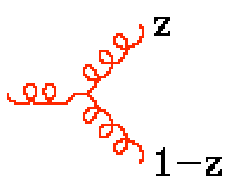
$P(z) \propto |\mathcal{M}(p_M \to p_A p_B)|^2$

Splitting function
IR singularity: z⇒0, 1

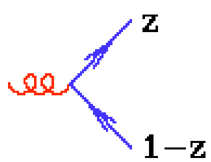
Splitting function, IR singular as z⇒0, 1 (mostly)



$$P_{q\to qg}(z) = C_F\,\frac{1+z^2}{1-z}, \qquad C_F = \frac{4}{3}$$



$$P_{g\to gg}(z) = C_A\left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right] \qquad C_A = 3$$



$$P_{g\to q\bar{q}}(z) = T_R\left[z^2 + (1-z)^2\right], \qquad T_R = \frac{1}{2}$$

Combining with

$$|\mathcal{M}_{n+1}|^2 d\Pi_{n+1} \simeq |\mathcal{M}_n|^2 d\Pi_n \frac{dt}{t}\frac{\alpha_S}{2\pi} P(z)\,dz\,d\phi$$

- ISR prefer soft(er), forward radiation.

Tagging ISR

D. Krohn, L. Randall, LTW, arXiv:1101.0810

- Initial identification
  - distinct in p_T OR
  - distinct in rapidity OR
  - distinct in m/p_T
- Check.
  - Not too central AND
  - Not too close to others. AND
  - Other jets similar, and central.

ISR tagging in more detail

- Distinct in p_T $\quad \frac{\max(p_{Ti}, p_{Tj})}{\min(p_{Ti}, p_{Tj})} > 2 \; \forall \; j \neq i$
- Distinct y $\quad |y_i - y_j| > 1.5 \; \forall \; j \neq i$
- Distinct Δ=m/p_T $\quad \frac{\max(\Delta_i, \Delta_j)}{\min(\Delta_i, \Delta_j)} > 1.5 \; \forall \; j \neq i$

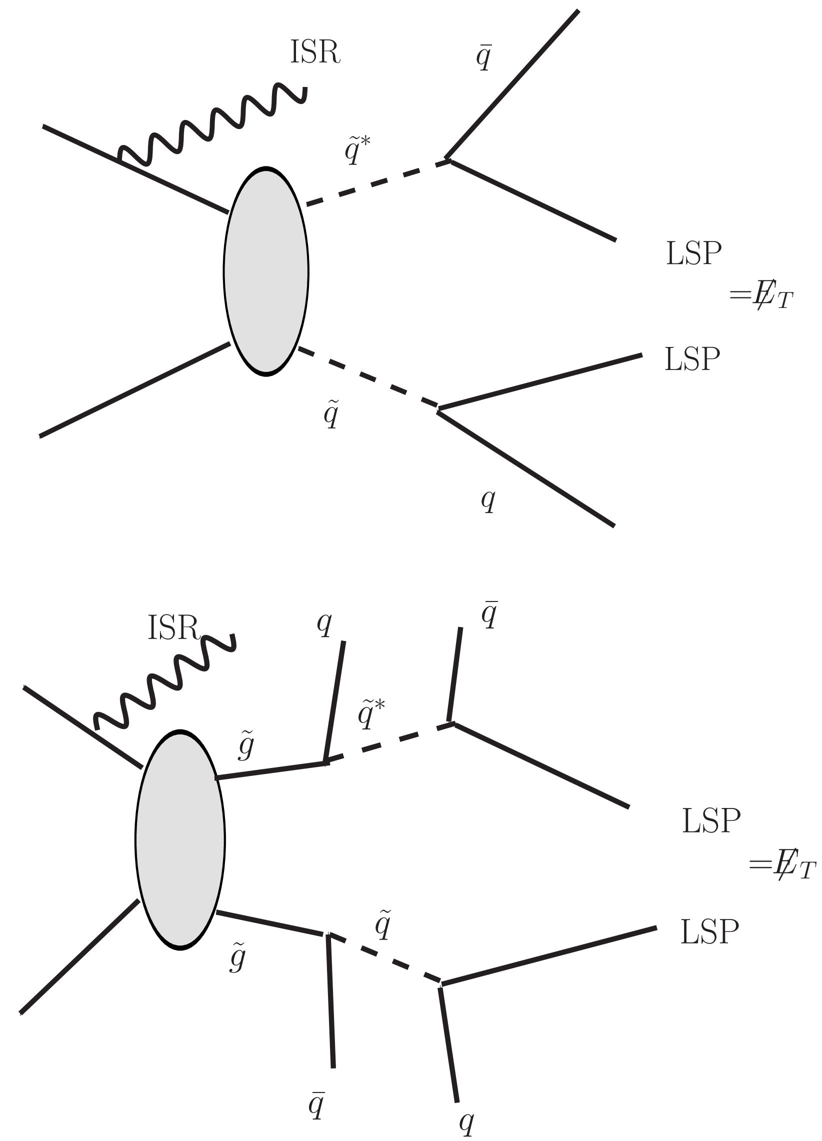
- Forward $\quad |y_i| > 1$
- Other jets similar $\quad |y_i - y_j| > 0.5 \; \forall \; j \neq i$

$$\frac{p_{Tj}}{p_{Tk}} < \rho + \frac{1/2}{1-\alpha} \qquad p_{Tj(k)} = \max(\min)\{p_{Tl} | \forall \; l \neq i\}$$

$$\rho = 2(3), \; \text{for}, \; N_f = 2(4)$$

Simple kinematical tagger works well.

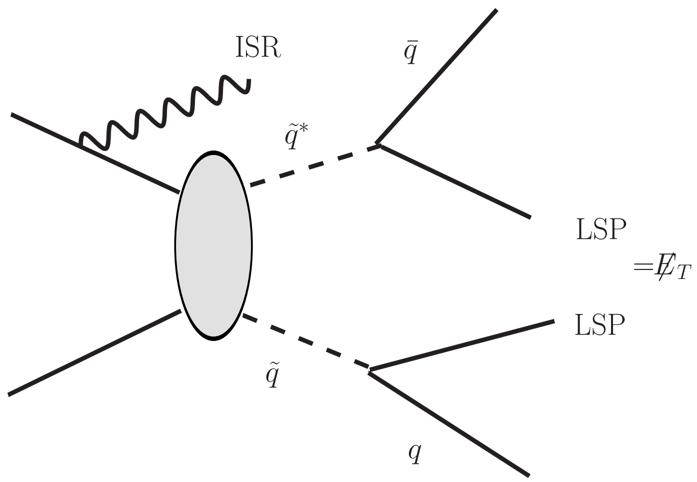
Spectrum		Efficiencies [%]	
$m_{\tilde{q}}/m_{\tilde{g}}$	m_{LSP}	Trigger	Mistag
500 GeV	100 GeV	42	15
500 GeV	450 GeV	42	12
1 TeV	100 GeV	41	11
1 TeV	950 GeV	41	9
500 GeV	100 GeV	13	22
500 GeV	400 GeV	15	10
1 TeV	100 GeV	12	25
1 TeV	900 GeV	16	8

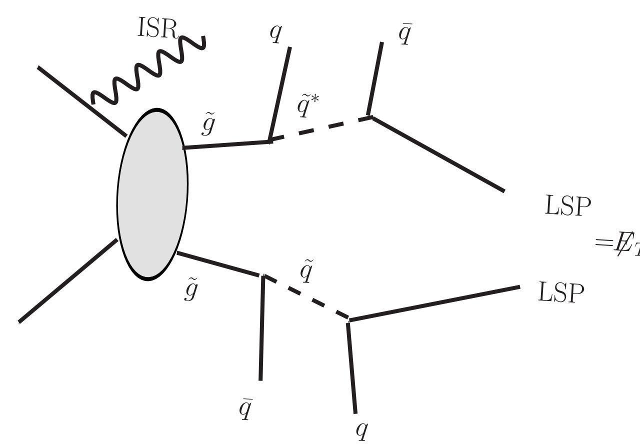


- Further developments.
  - Asymmetric toplogy?
  - More inclusive?

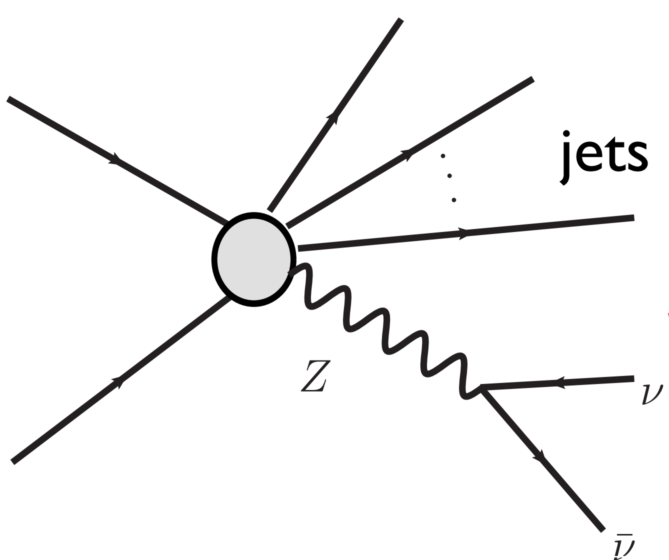
Utility of ISR tagging

- Enhance signal/background.



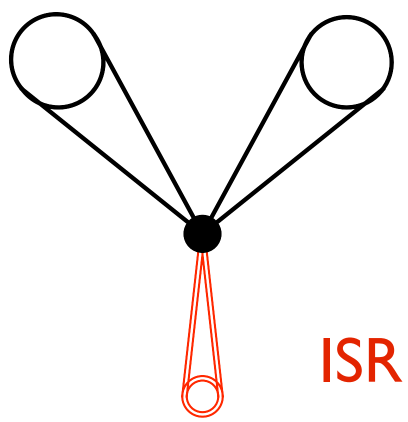


ISR, correlated with masses, and color o f squark and gluino
FSR, controlled by the mass differences $m_{\tilde{g},\tilde{q}} - m_{\mathrm{LSP}}$



Jets more or less similar to each other in the background

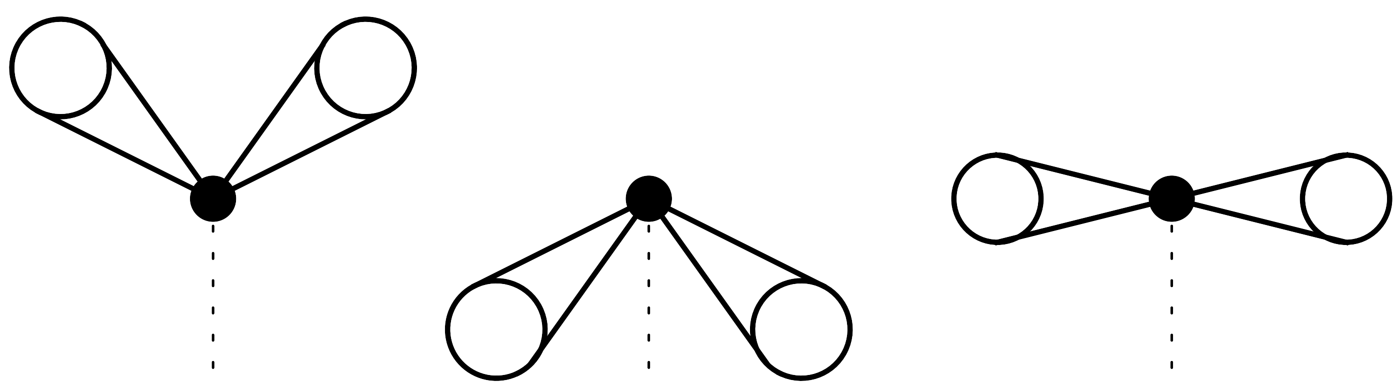
Mass measurement.



A system with invariant mass M_0
including visible+invisible

For any FSR with $p_{\bar{T}_i} = \vec{p}_{T_i} \cdot \hat{p}_T^{\rm ISR}$, and assuming $M_{\rm test}$,

$$p_{\bar{T}_i} \to \frac{p_T^{\rm ISR}}{M_{\rm test}} E_i + \sqrt{1 + \left(p_T^{\rm ISR}/M_{\rm test}\right)^2}\, p_{\bar{T}_i}.$$

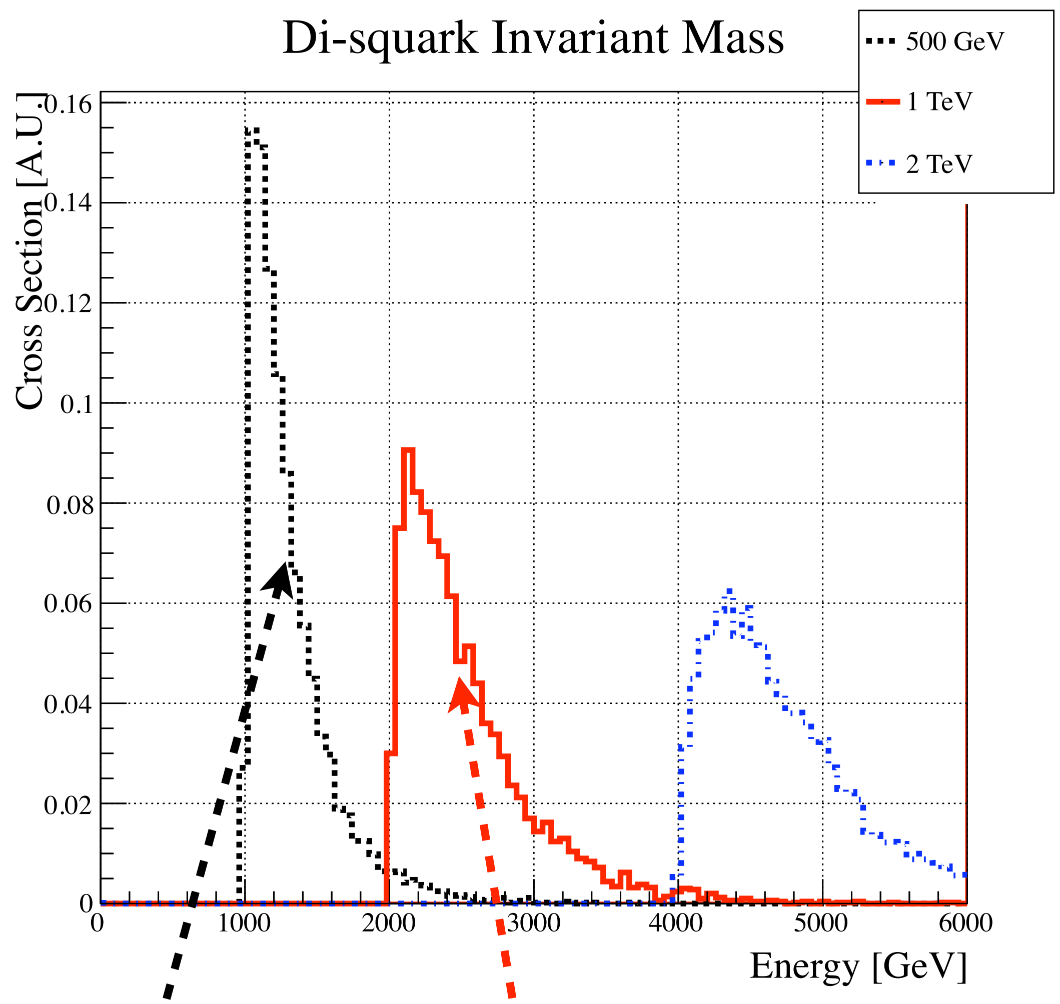


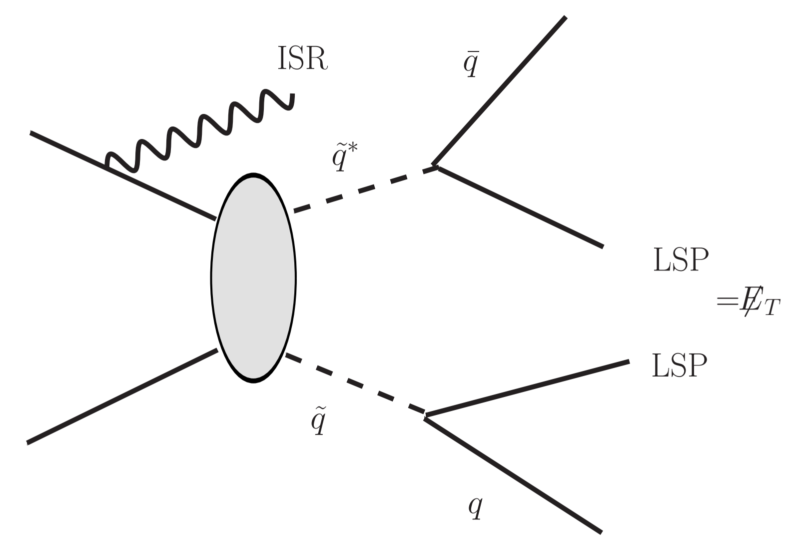
under boost   over boost $M_{\rm test}$=M_0

Example: squark pair production

- Produced near threshold, mass of 2 squark system

$$M_0 \sim 2m_{\tilde{q}}$$

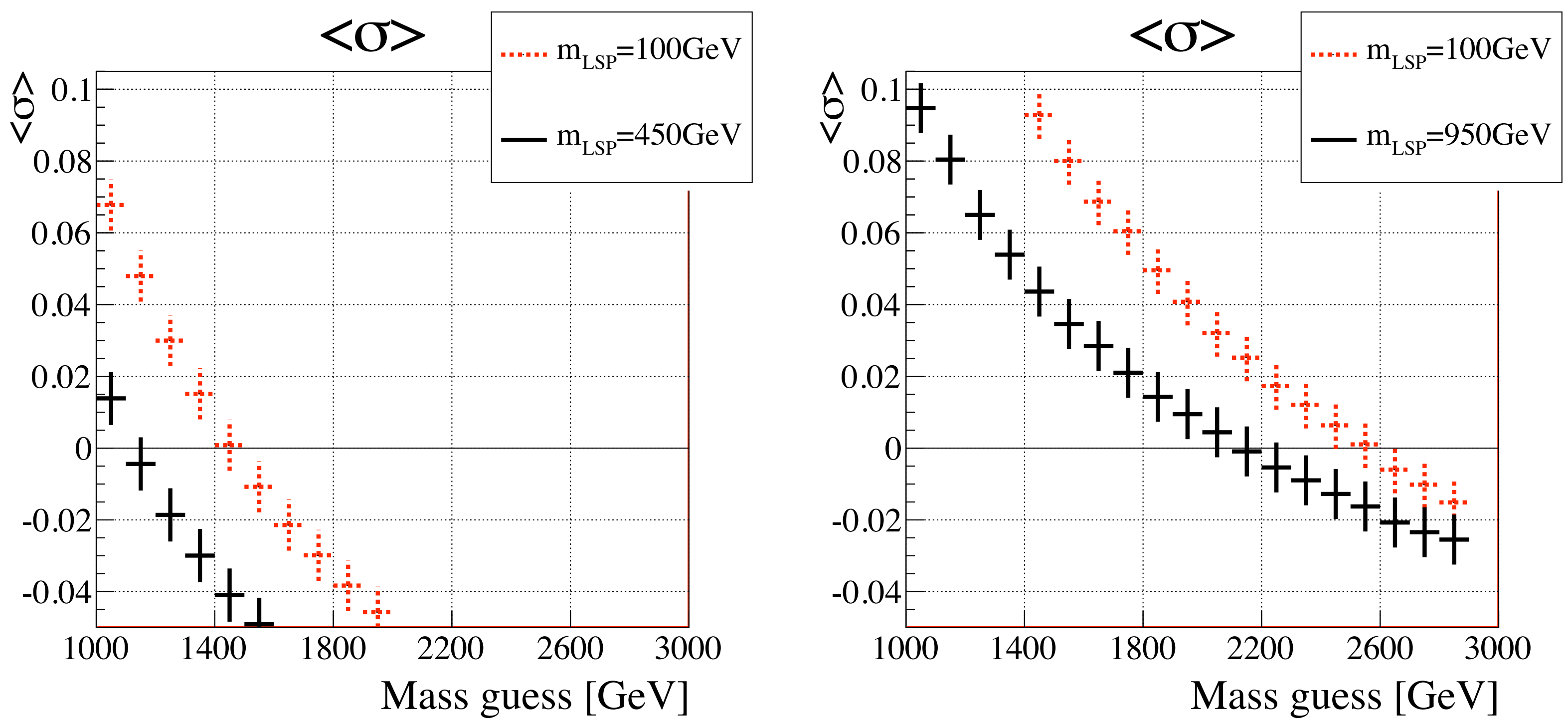




$m_{\tilde{q}} = 500$ GeV
$M_0 \sim 1.2$ TeV

$m_{\tilde{q}} = 1$ TeV
$M_0 \sim 2.5$ TeV

Examples: squark pair production



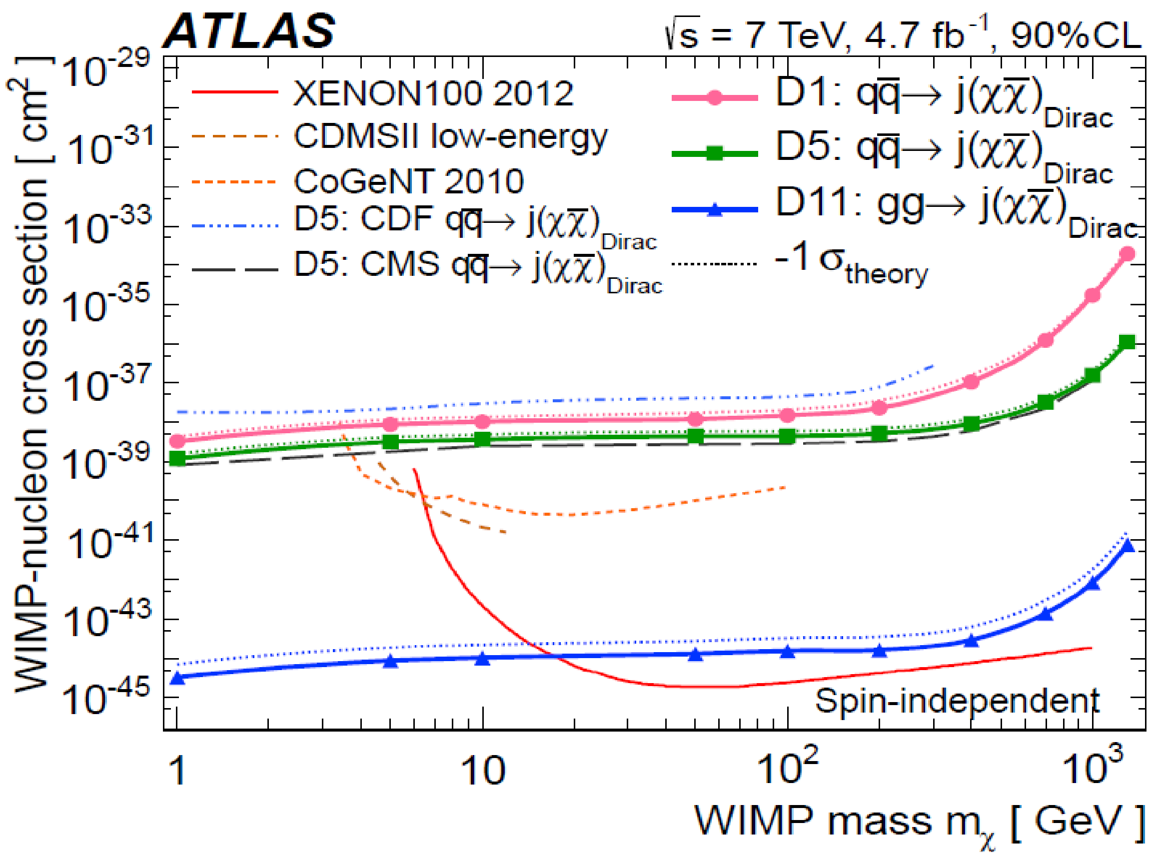
$$m_{\tilde{q}} = 500 \text{ GeV}$$
$$M_0 \sim 1.2 \text{ TeV}$$

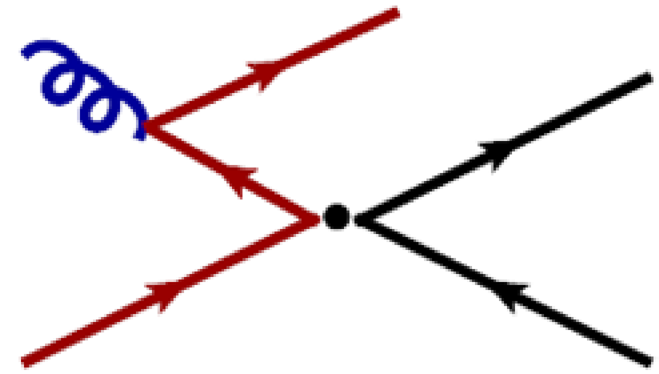
$$m_{\tilde{q}} = 1 \text{ TeV}$$
$$M_0 \sim 2.5 \text{ TeV}$$

$$\sigma = +1 \ (-1) \text{ if } \sum_i p_{\bar{T}_i} > 0 \ (< 0), \ \langle \sigma \rangle = \sum_{j=1}^{N} \sigma_j / N$$

Production near the threshold, mass of the 2 squark system $M_0 \sim 2m_{\tilde{q}}$

ISR as monojet

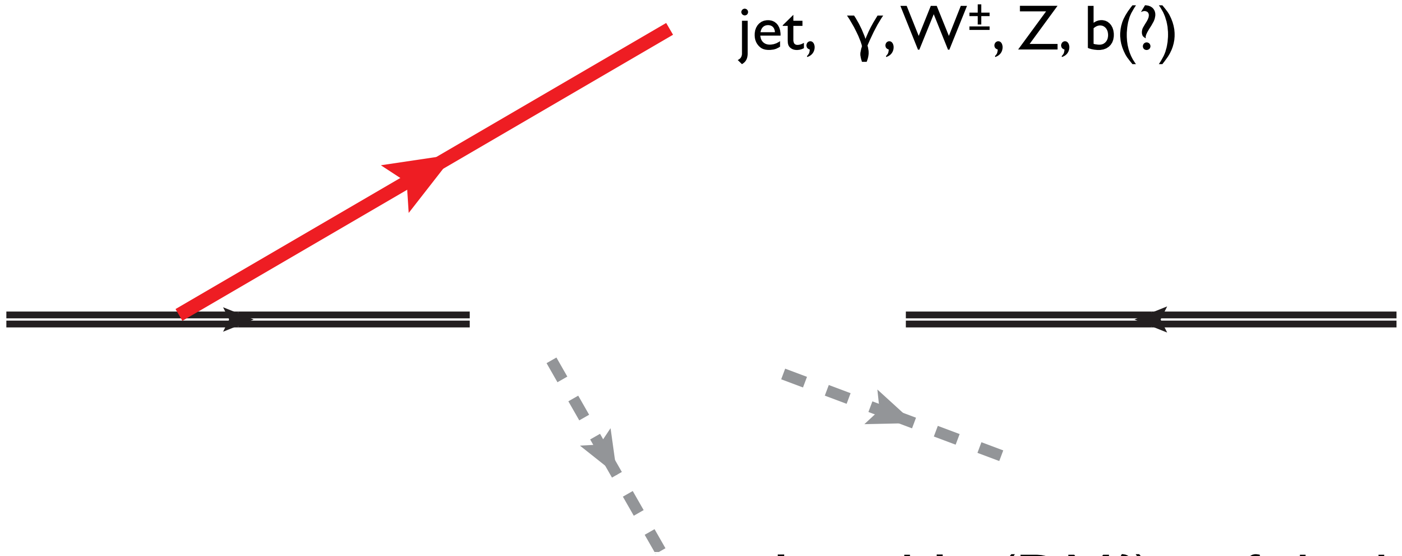




- Detailed improvements possible.
  - Effect of light mediator.

For example, An, Ji, LTW, 1202.2894, Fox, Harnik, Kopp, Tsai, 1103.0240, Goodman, Shepherd, 1111.2359

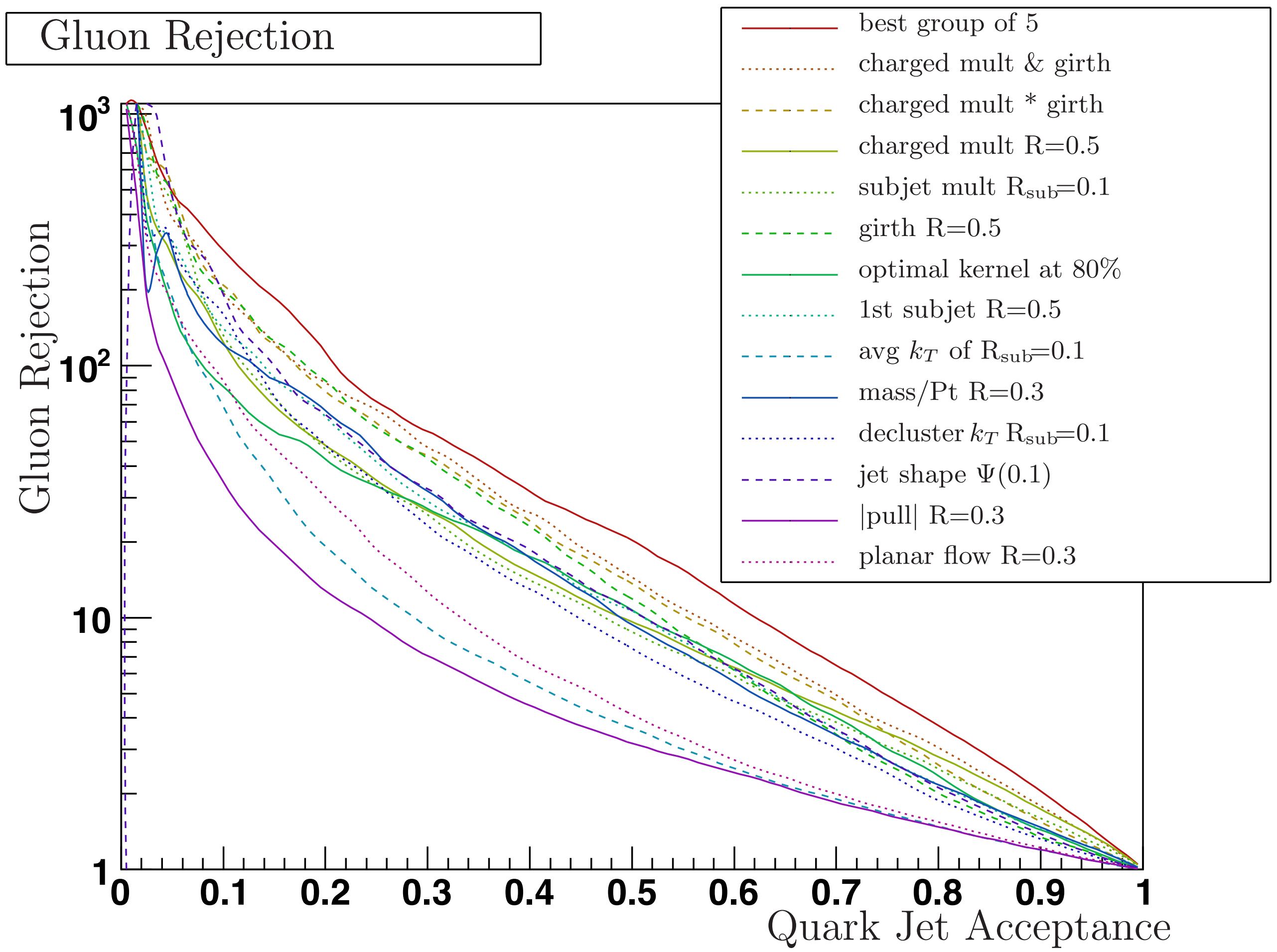
ISR + soft(not so hard) objects



- ISR + soft lepton etc.
- ISR + soft jet ...
  - ISR tagger can help.

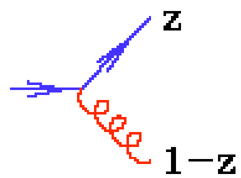
q/g of jet

- Addition properties of jet: quark or gluon.
  - Can improve, for example, SUSY gluino signal...
- Quark gluon taggers.



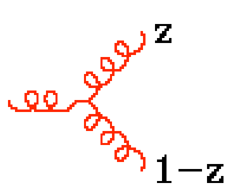
Gallicchio, Schwartz, 1211.7038

q/g of ISR.



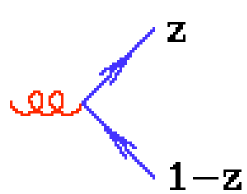
$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z} \qquad C_F = \frac{4}{3}$$

radiated gluon wants to be soft



$$P_{g\to gg}(z) = C_A \left[\frac{z}{1-z} + \frac{z}{1-z} + z(1-z)\right] \qquad C_A = 3$$

one of the gluons wants to be soft

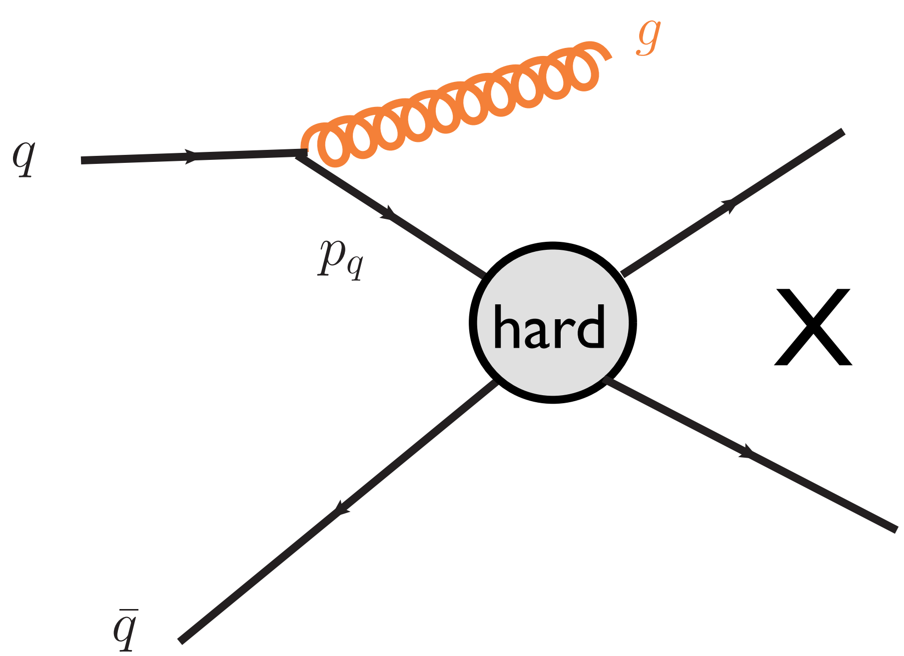


$$P_{g\to q\bar{q}}(z) = T_R \left[z^2 + (1-z)^2\right] \qquad T_R = \frac{1}{2}$$

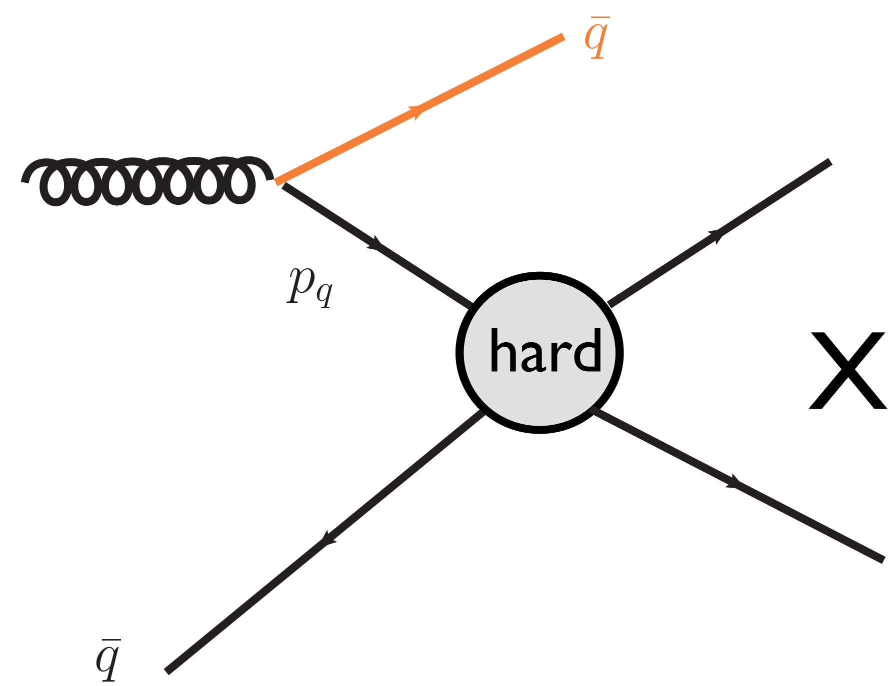
no soft enhancement. both hard

q+qbar⇒X hard interaction.

$$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$$

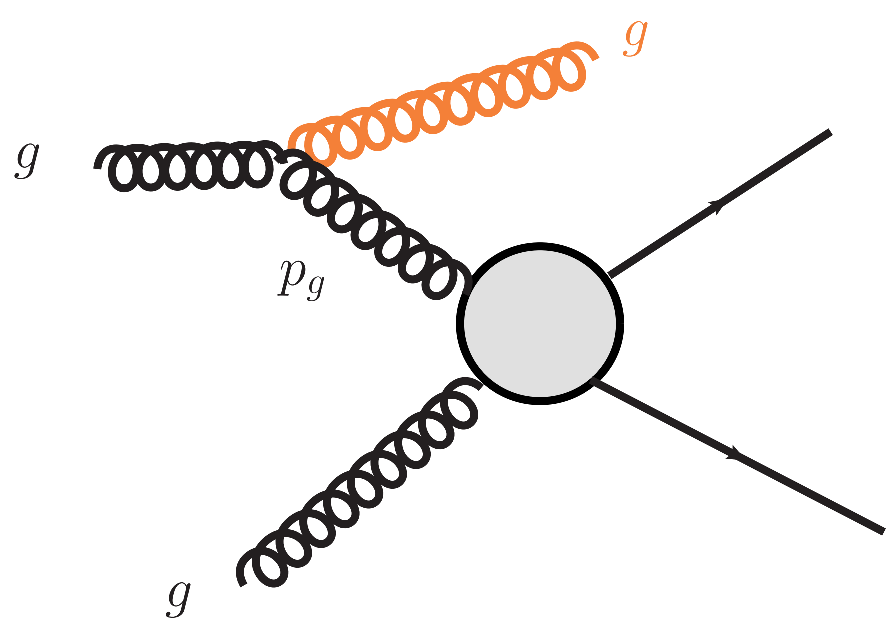


$$P_{g\to q\bar{q}}(z) = T_R\left[z^2 + (1-z)^2\right]$$



- p_q is on the order of the E_{cm} (hard).
- quark (jet) ISR tends to be harder.
- Convolution of PDF, C_F vs T_R, important.

g+g⇒X hard interaction



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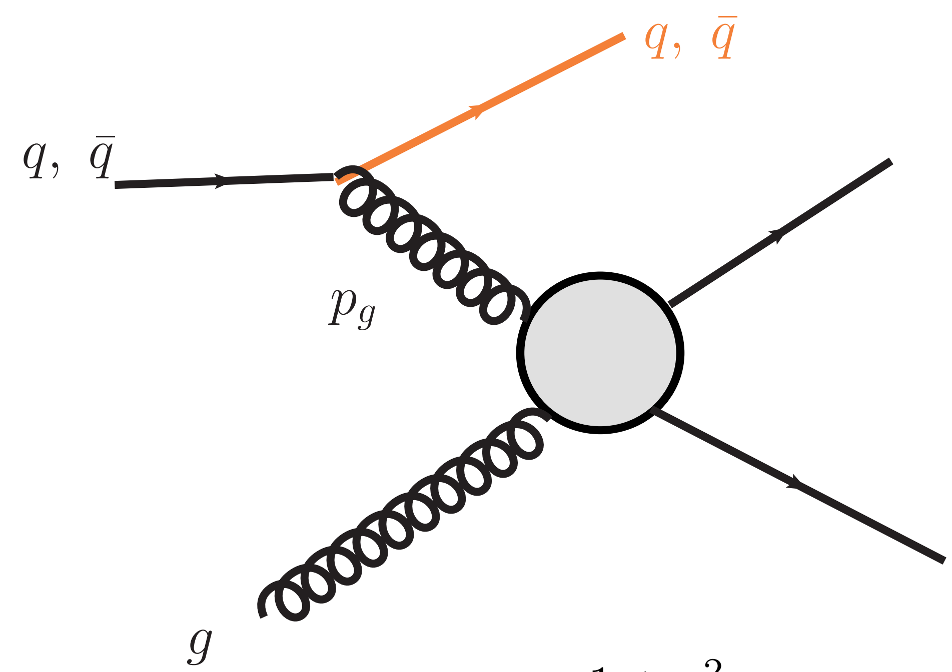

$$P_{q\to qg}(z) = C_F\frac{1+z^2}{1-z}$$

- gluon ISR wants to be soft.
- quark ISR harder.
- Different from qqbar⇒X (PDF, C_A vs C_F).

Conclusions.

- Discovering Weak scale new physics likely to be challenging.
  - Hidden in hadronic final states?
- Initial state radiation is an integral part of such signals.
  - Tagging ISR.
  - Using ISR to better characterize the signal.
- Many detailed study necessary.